

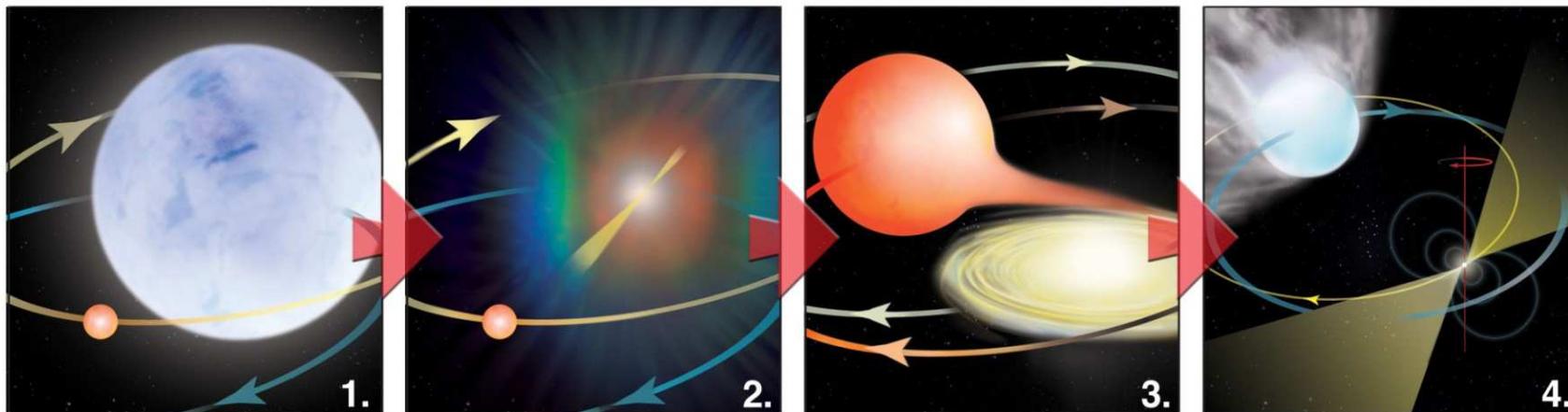
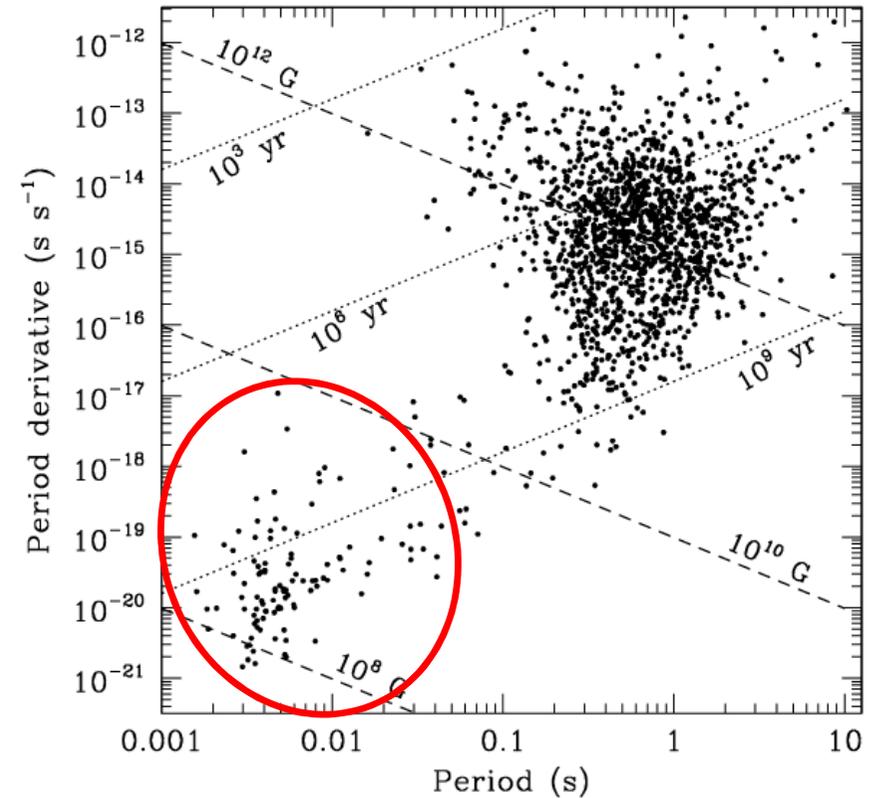
Transitional Millisecond Pulsars:
A Population of γ -ray-Emitting
Low-mass X-ray Binaries

Slavko Bogdanov



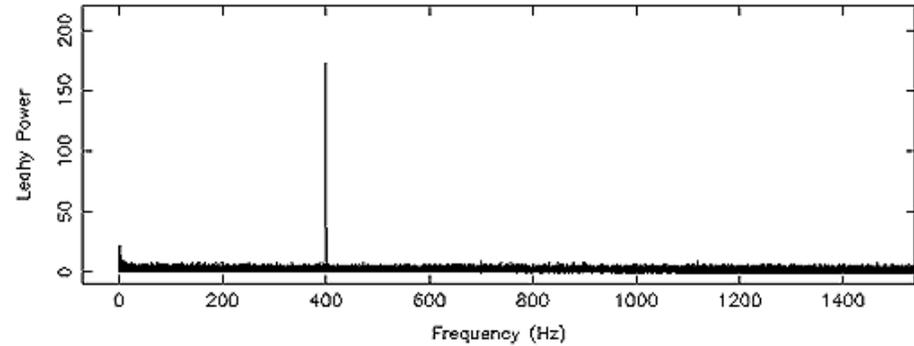
Rotation-powered (“recycled”) millisecond pulsars

- Discovered at radio frequencies
 - PSR B1937+21 with Arecibo (Backer et al. 1982)
- Most radio MSPs are in binaries
- Spun-up (“recycled”) by accretion in LMXBs (Alpar et al. 1982)

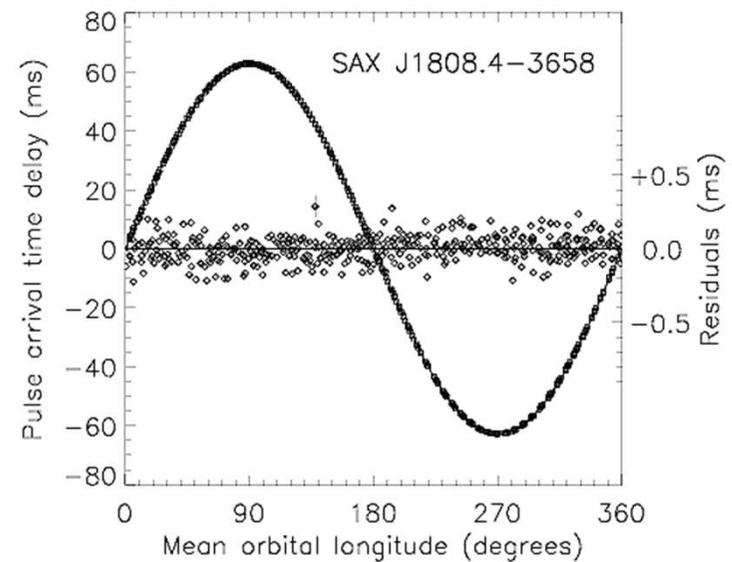
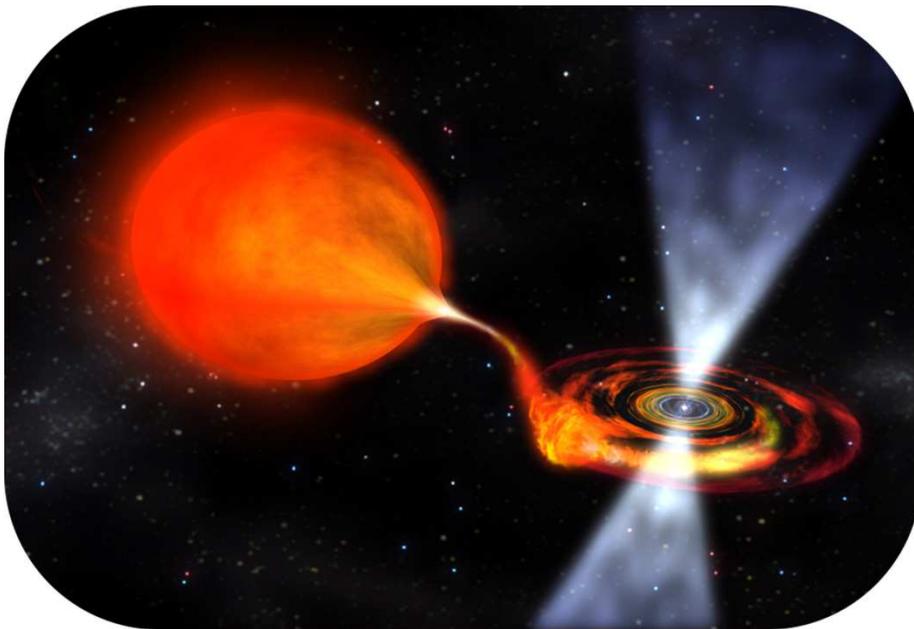


Accretion Powered MSPs: SAX J1808.4–3658

- First accretion-powered MSP
($\nu = 408$ Hz)



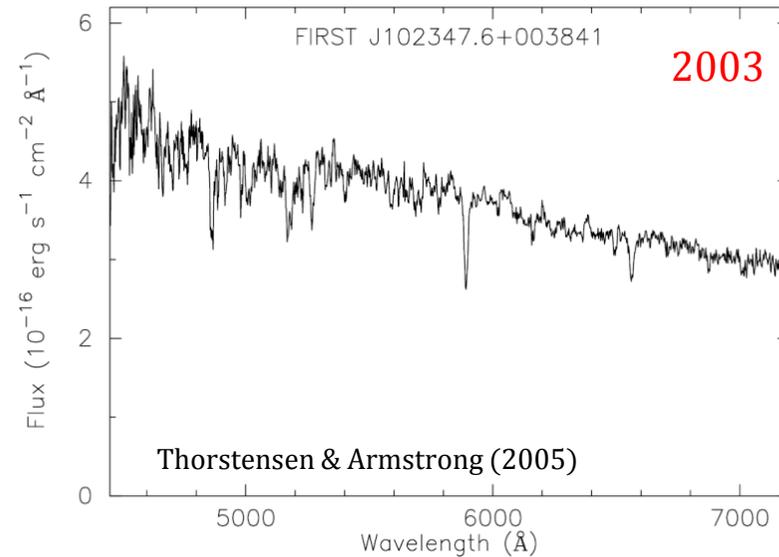
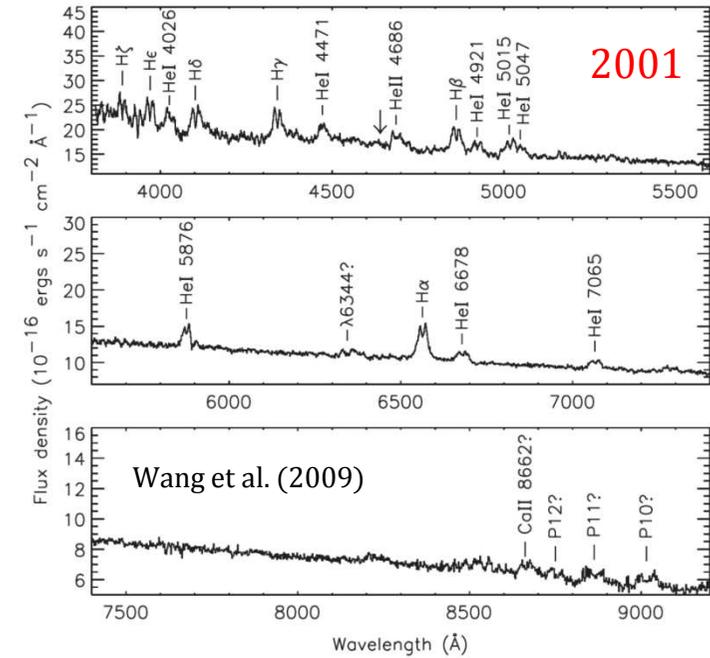
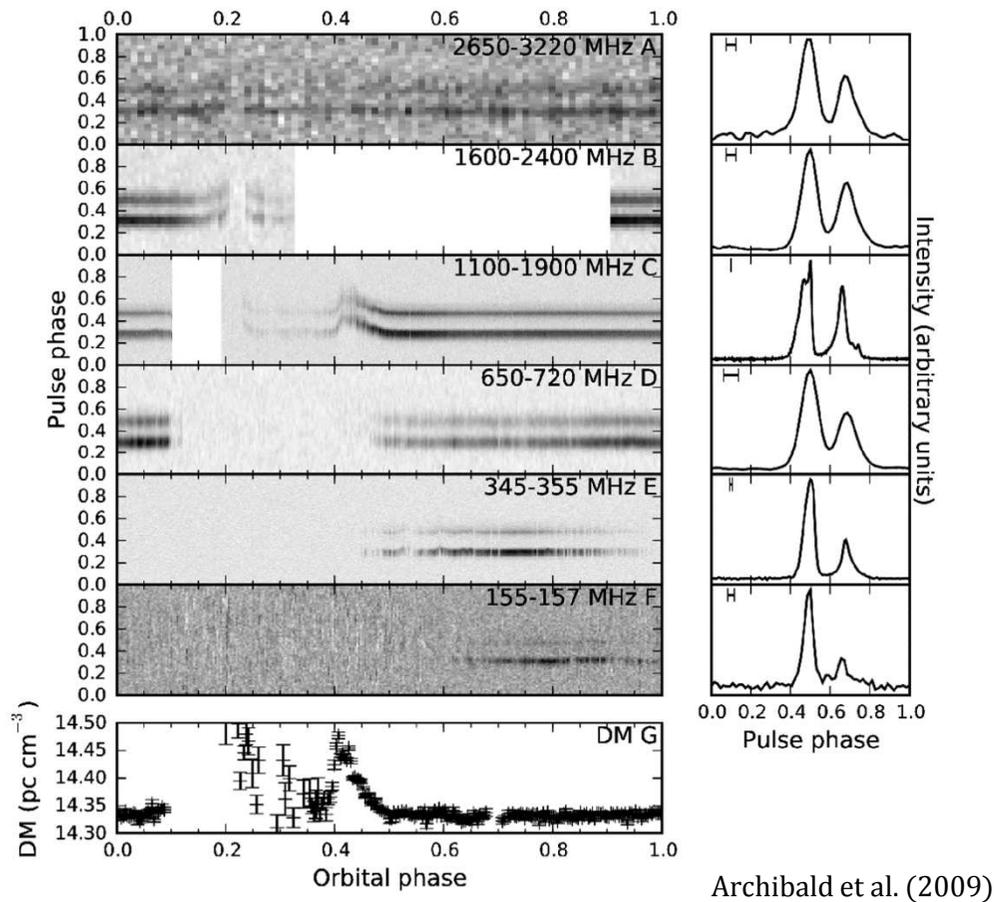
Wijnands & van der Klis 1998, *Nature*, 394, 344



Chakrabarty & Morgan 1998, *Nature*, 394, 346

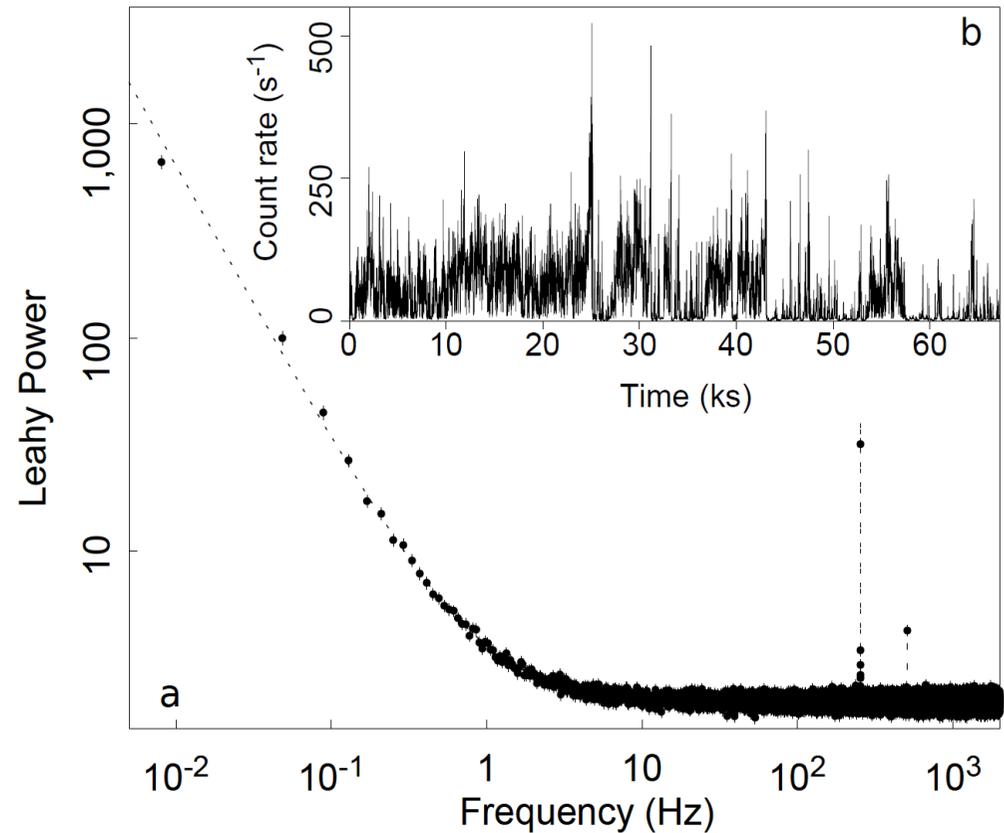
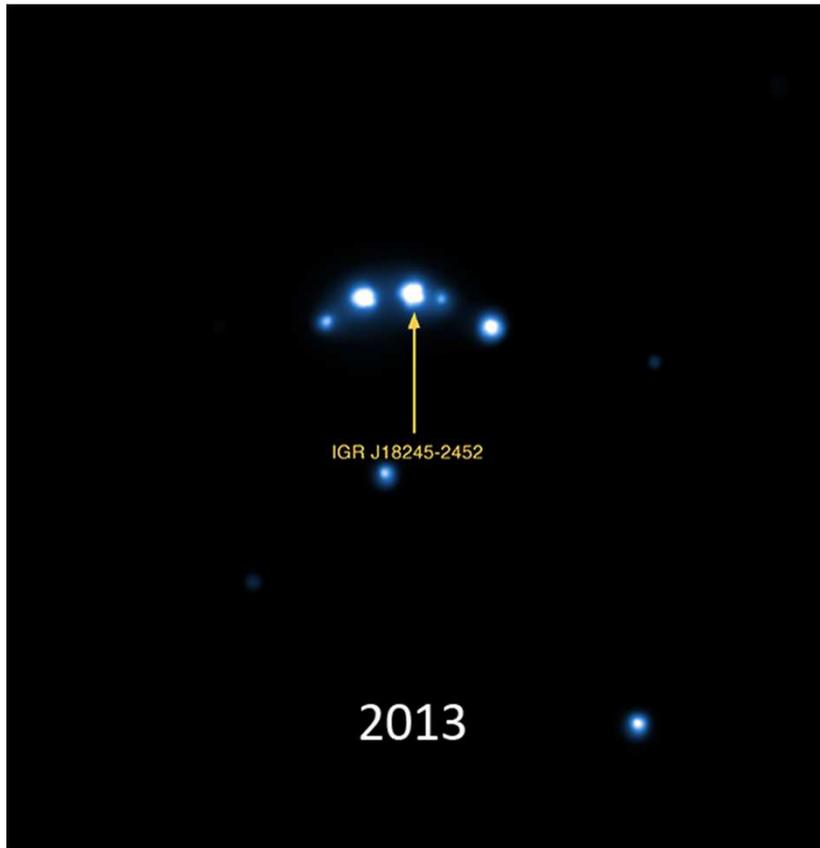
PSR J1023+0038: The “Missing Link”

- System had accretion disk in 2001 but not after 2003
- Eclipsing (“redback”) binary radio MSP ($P = 1.69$ ms, $P_b = 4.8$ d) discovered in 2009



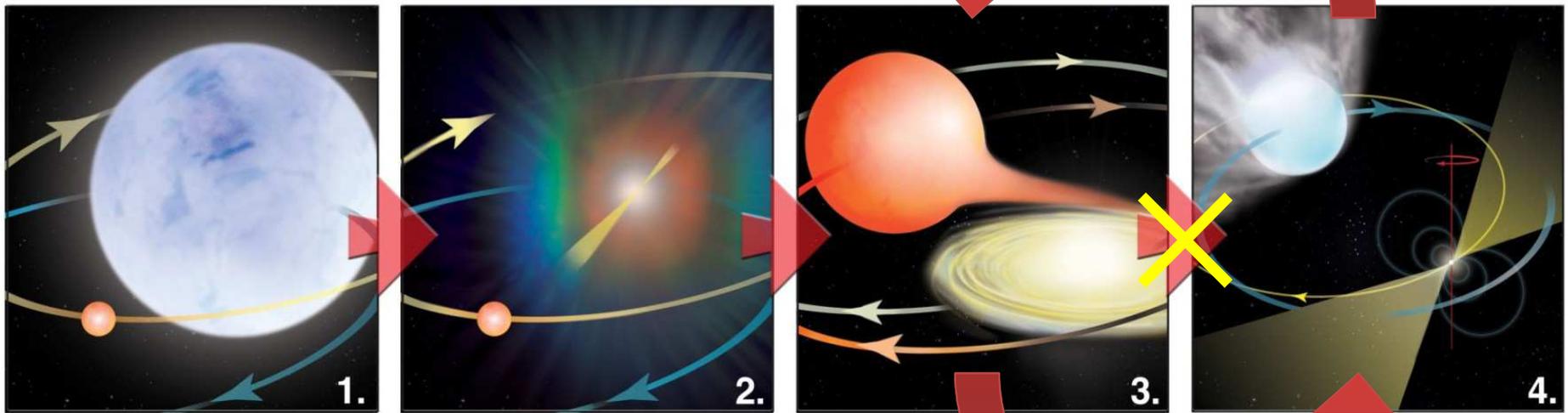
PSR J1824–2452I / IGR J18245–2452 (M28)

Rotation-powered (radio) MSP \leftrightarrow Luminous accretion-powered (X-ray) MSP



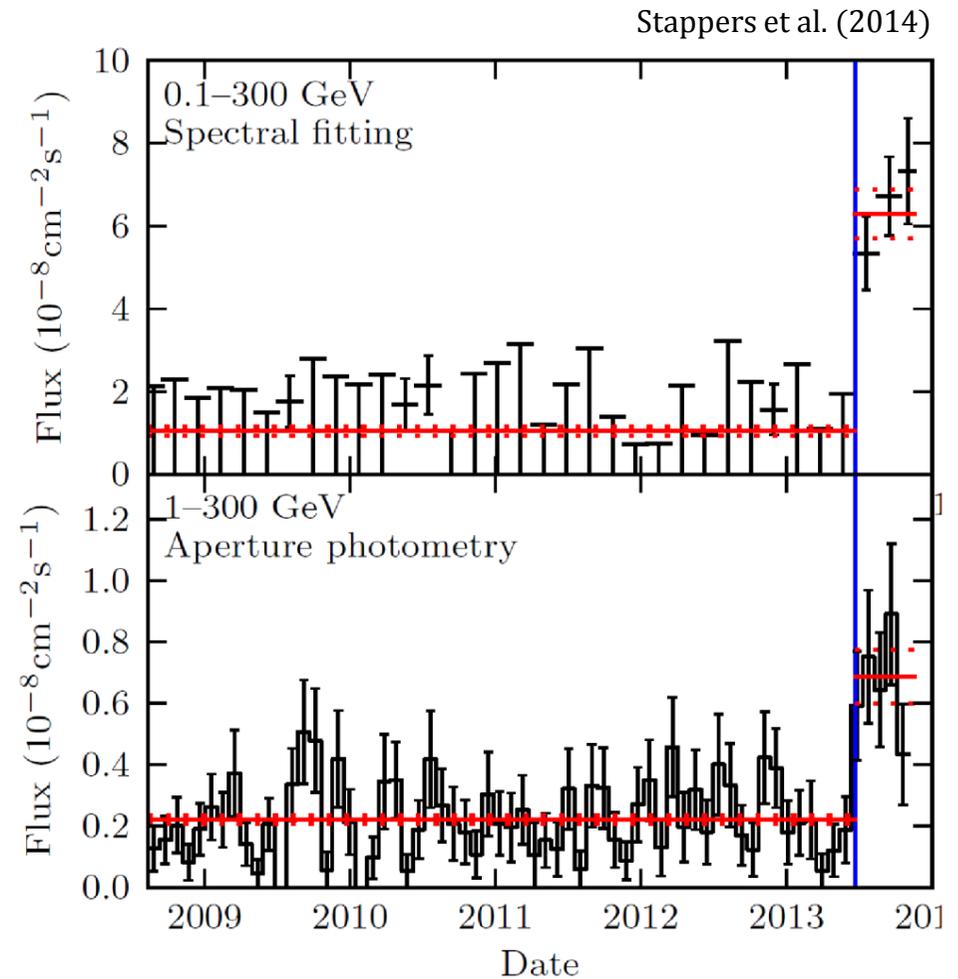
Papitto et al. (2013)

Direct link between low-mass X-ray binaries and “recycled” millisecond pulsars

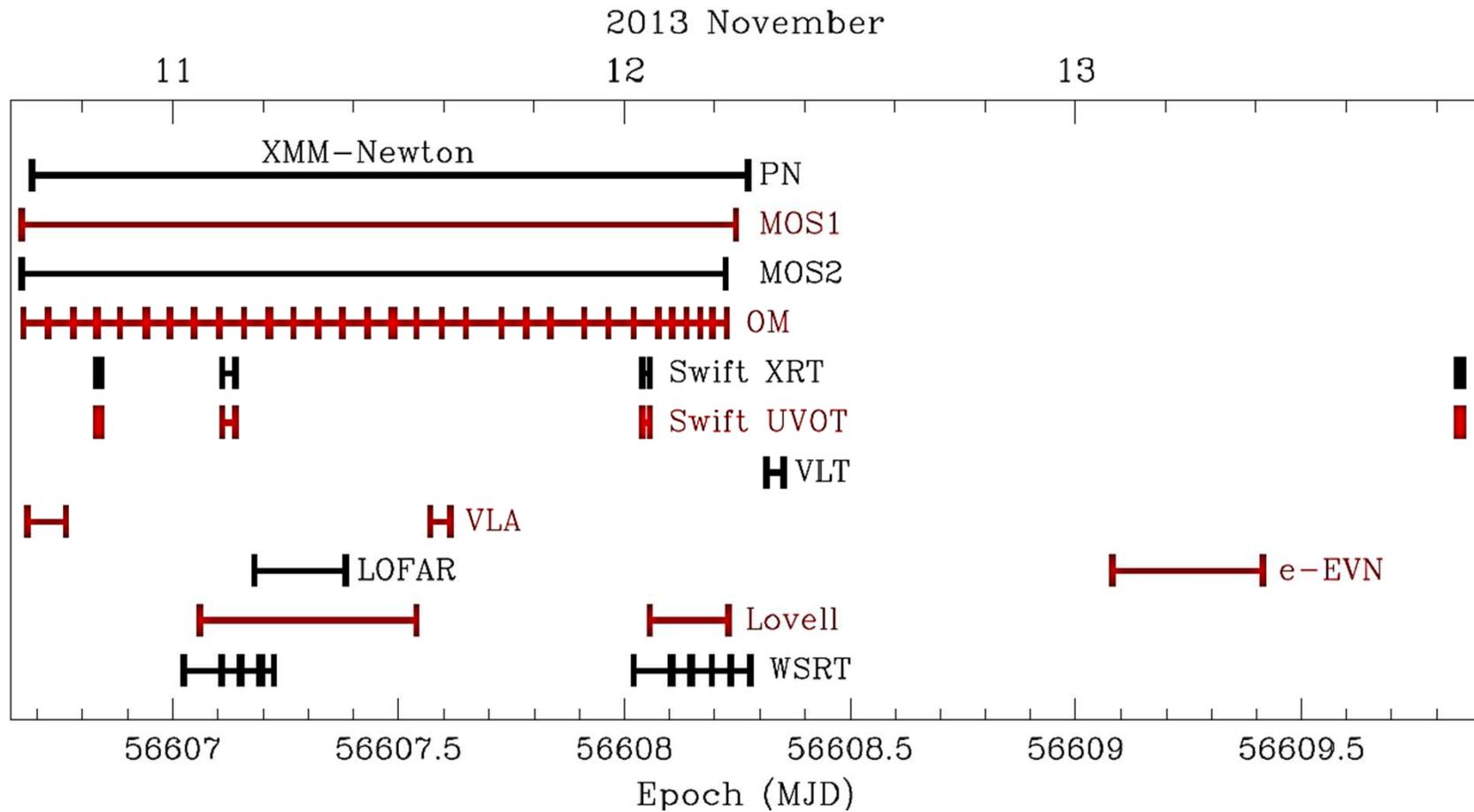


PSR J1023+0038: The Accretion Disk Returns

- Radio pulsar emission ceased on June 23rd, 2013
- Optical brightness increased by ~ 1 mag
- Double-peaked optical emission lines reappeared
- Average X-ray flux increased by \sim order of magnitude
- *Fermi* LAT flux increased ≈ 5 -fold!



PSR J1023+0038: The Accretion Disk Returns



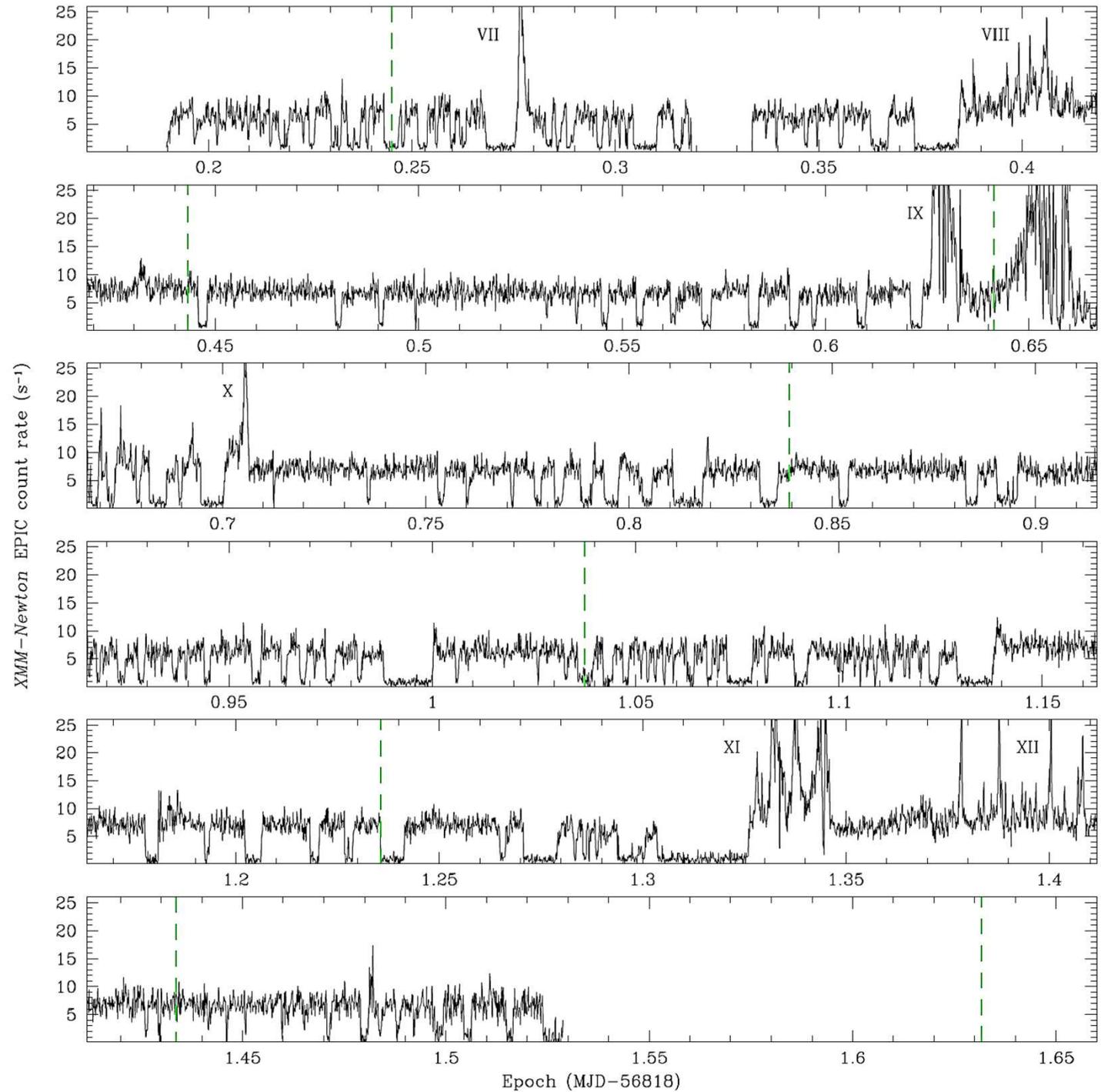
PSR J1023+0038

XMM-Newton EPIC

Jun 10th, 2014

117 ks

$L_X \approx 10^{33-34} \text{ erg s}^{-1}$
(0.3–10 keV)

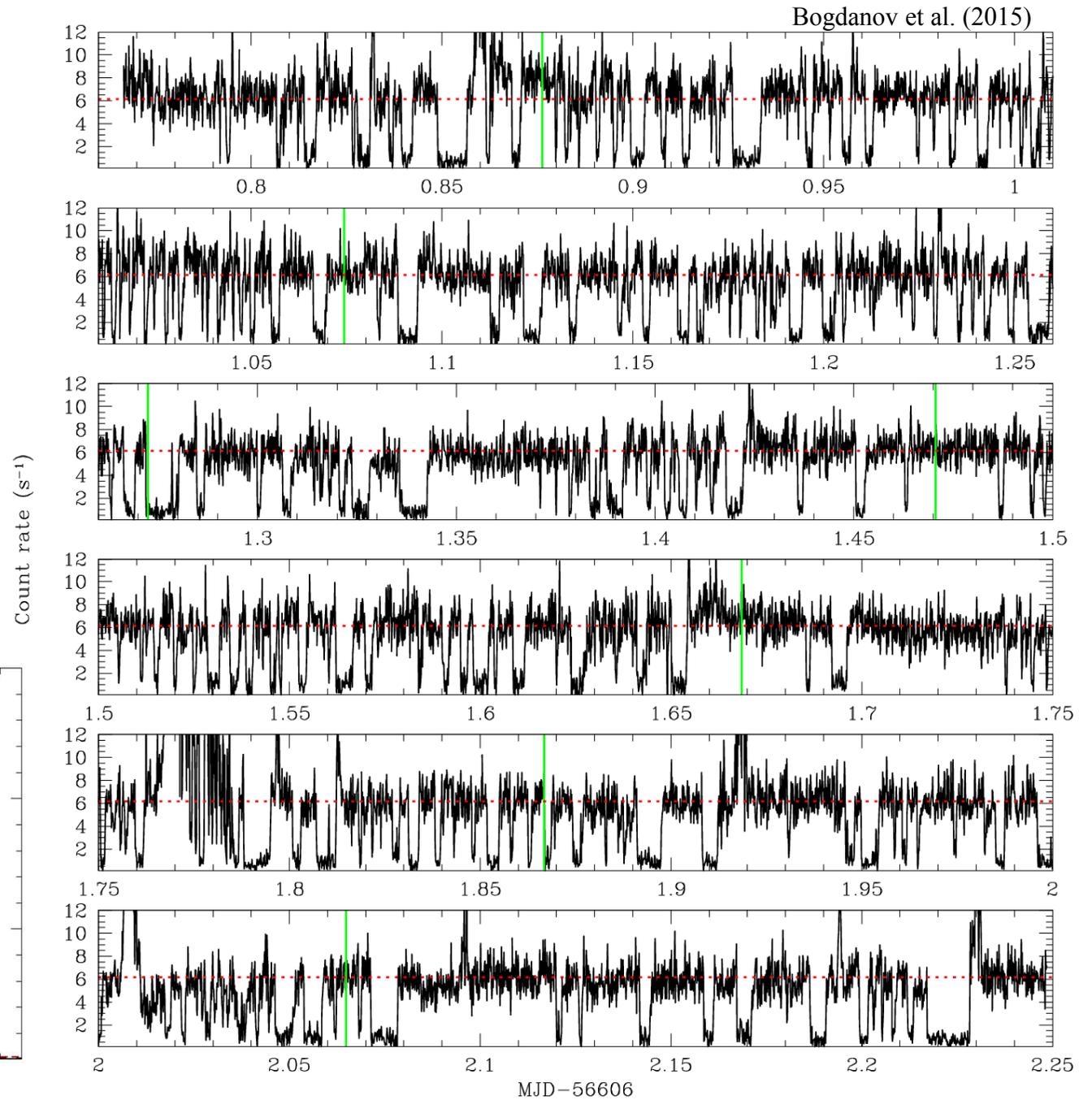
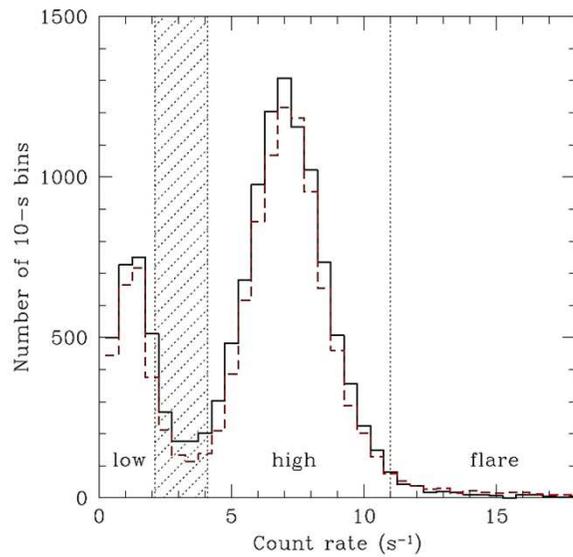


Bogdanov et al. (2015)

XMM-Newton EPIC

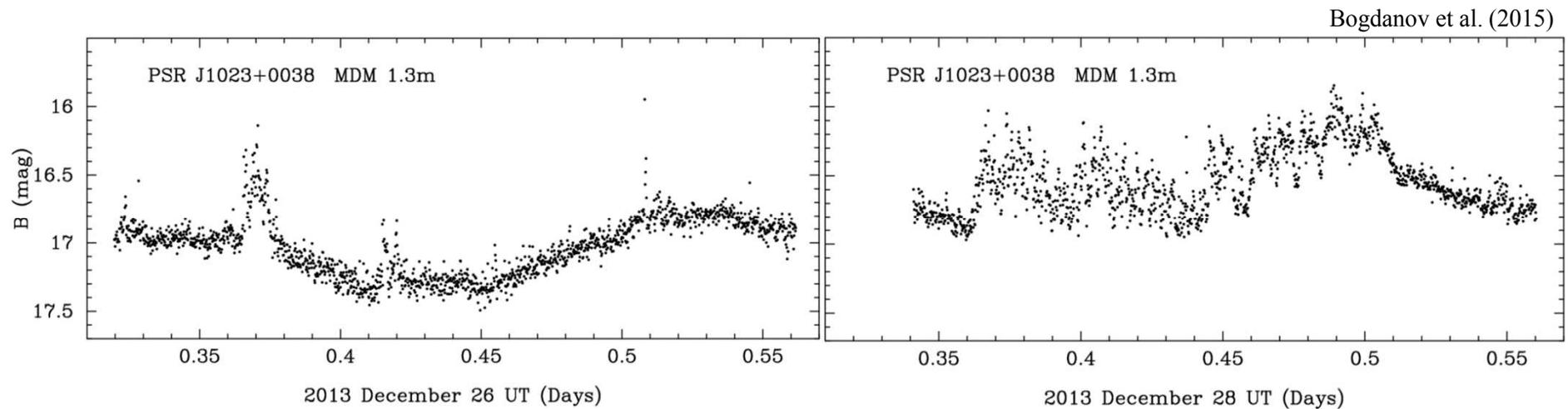
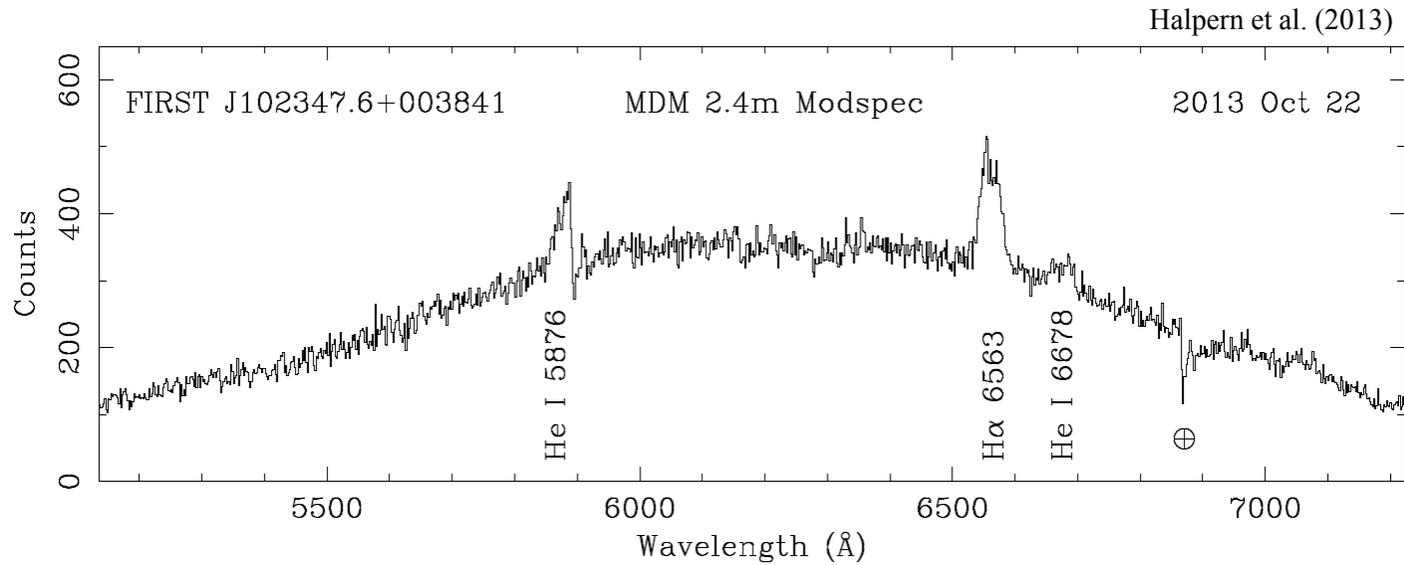
Nov 10th, 2013

134 ks



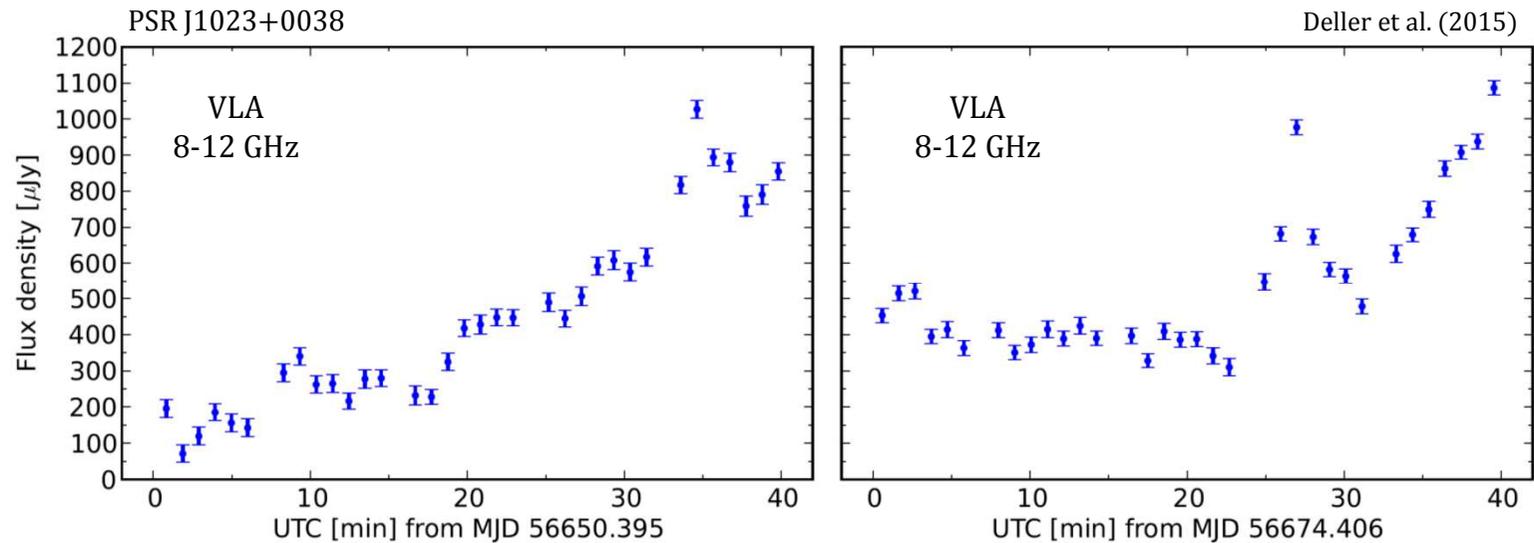
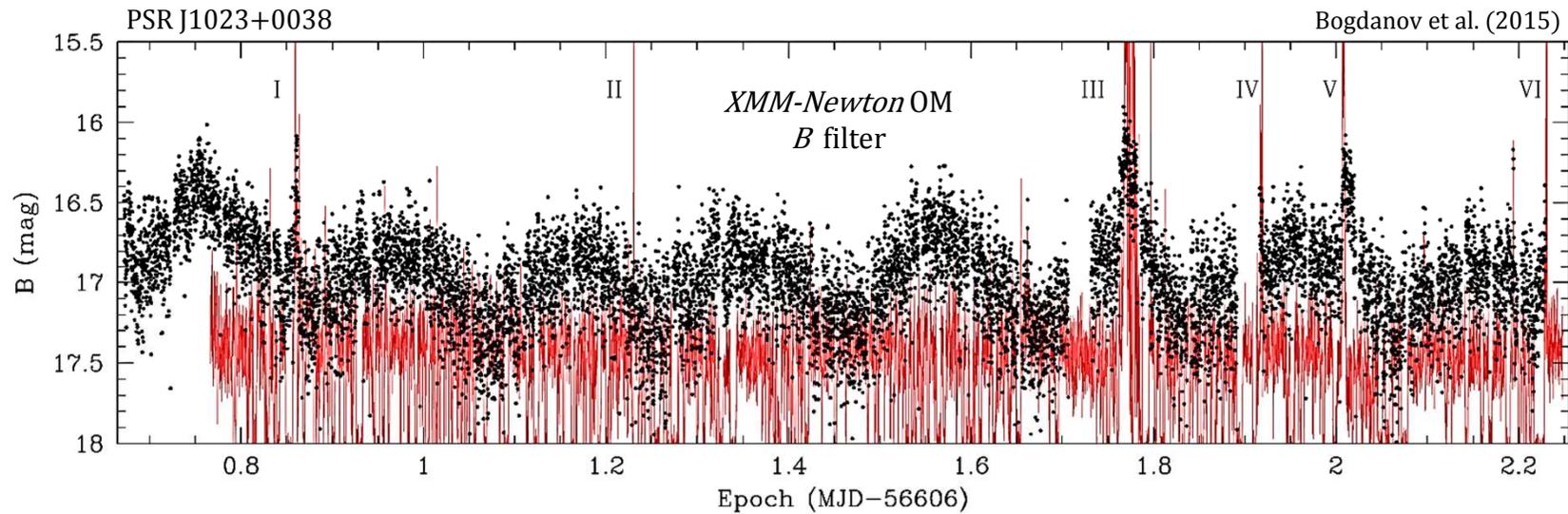
PSR J1023+0038: The Accretion Disk Returns

- “CV-like” optical properties



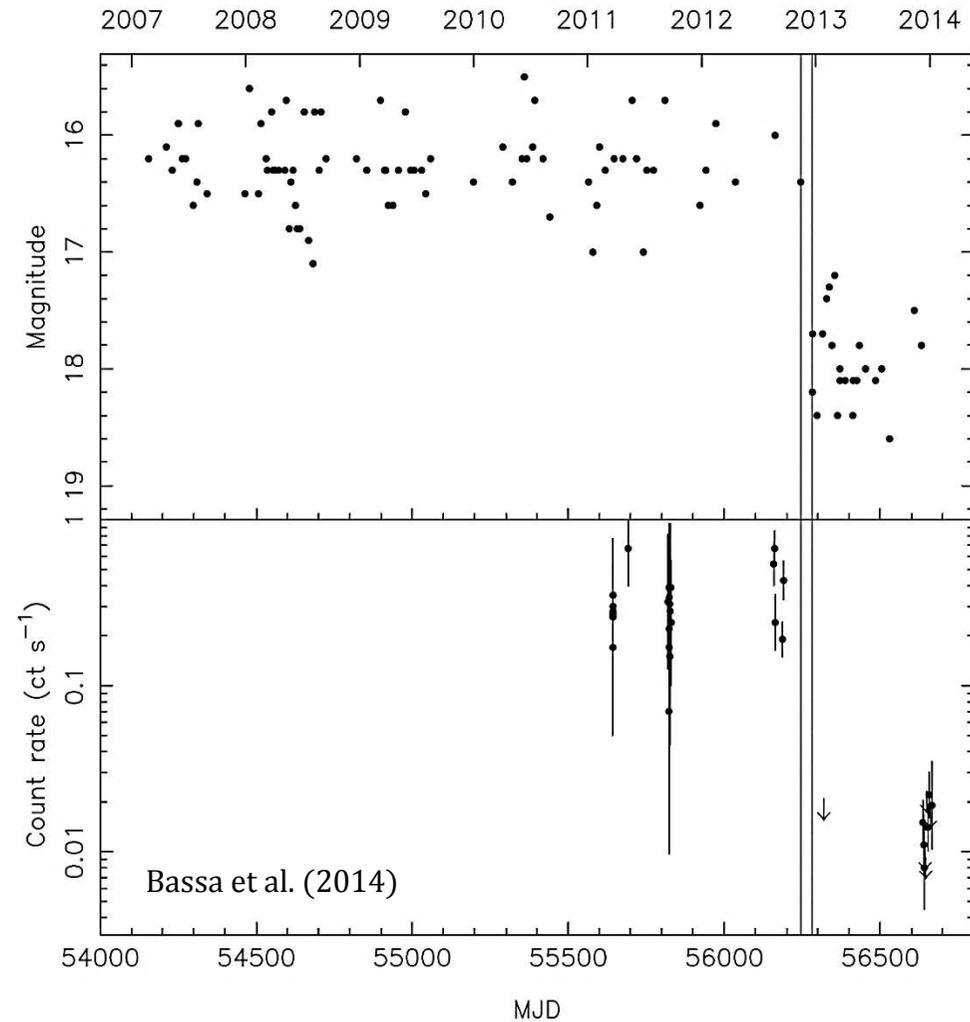
PSR J1023+0038: The Accretion Disk Returns

- X-ray, optical and radio variability



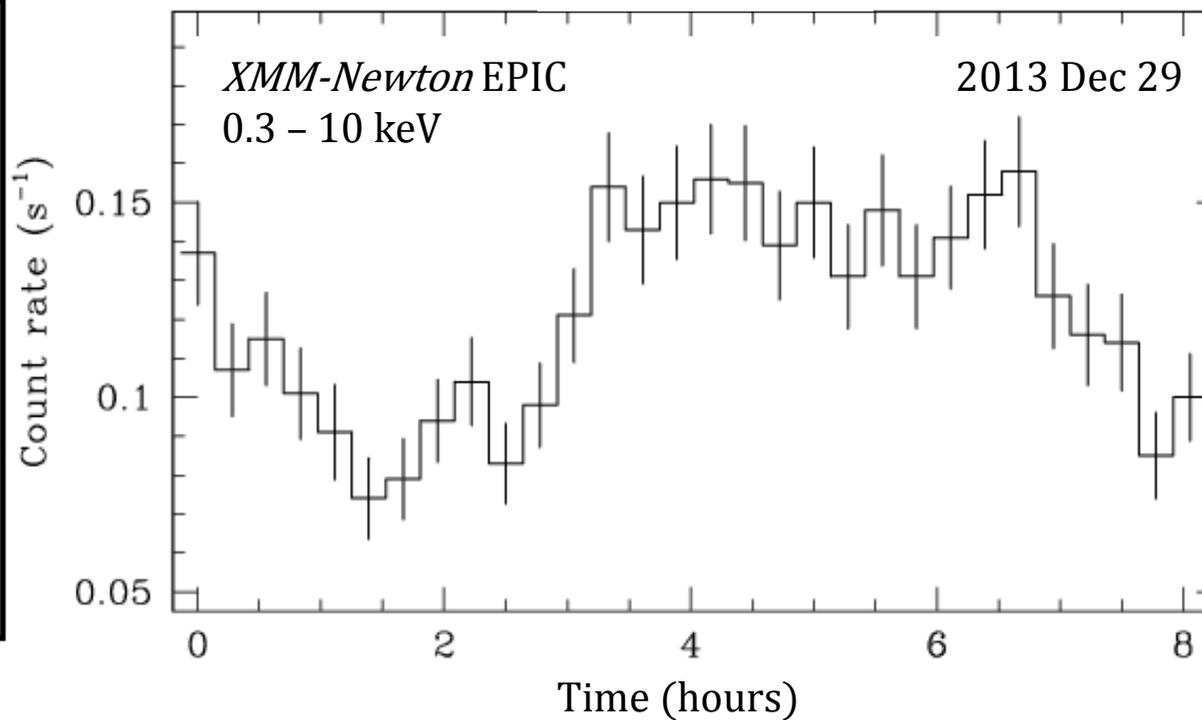
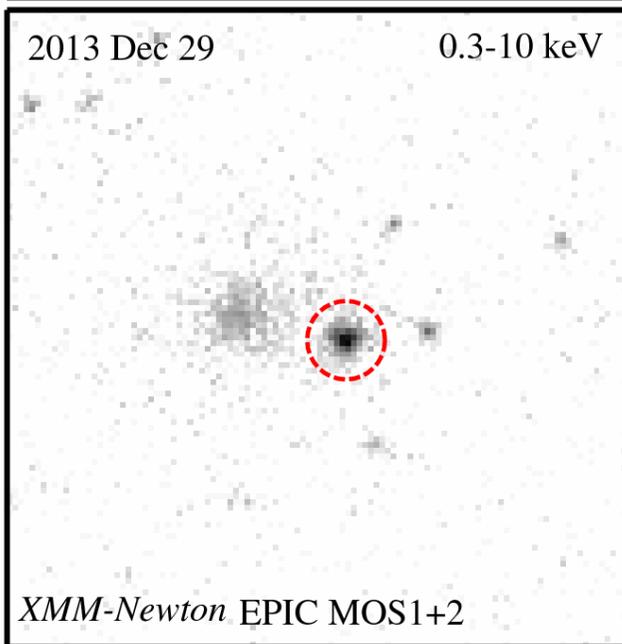
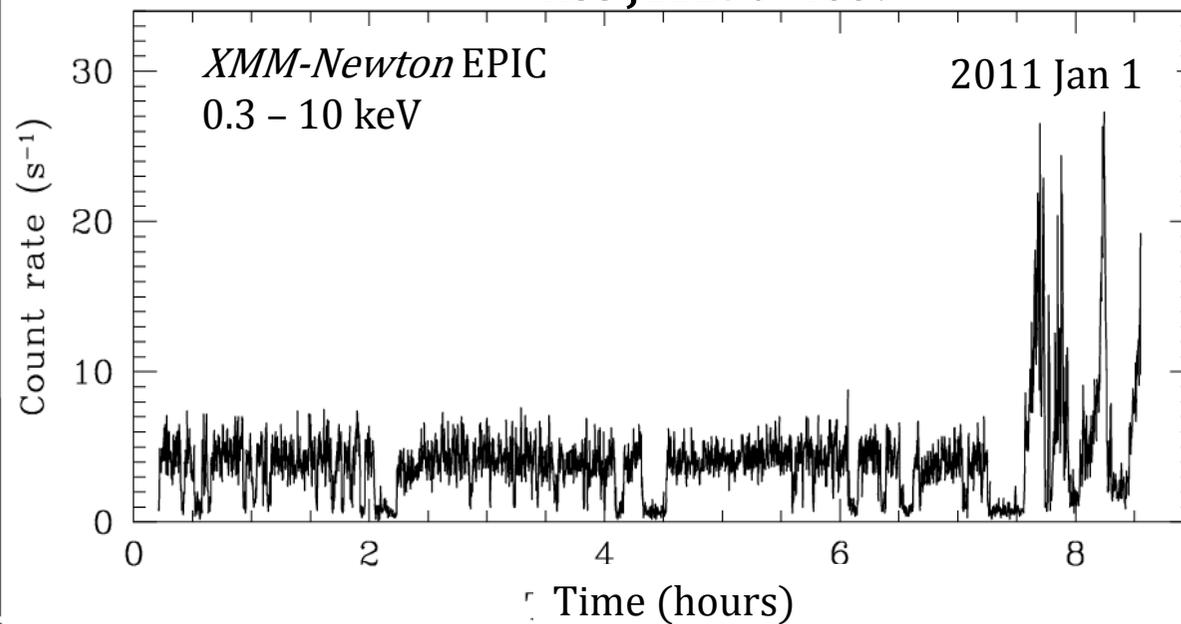
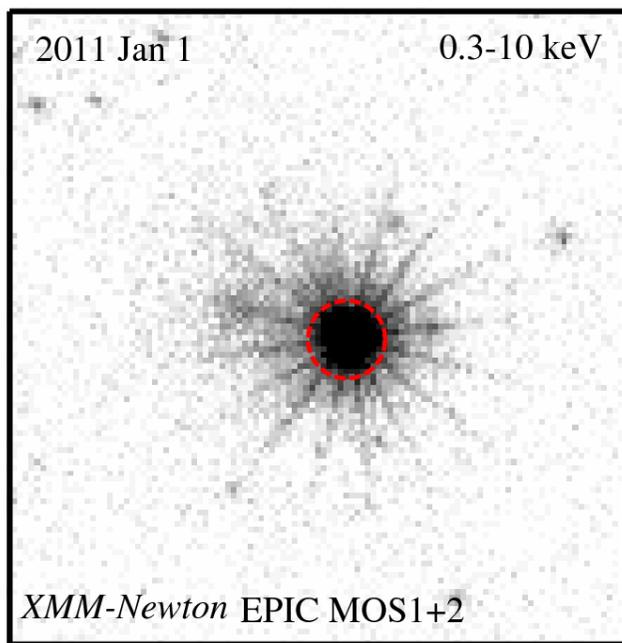
XSS J12270–4859: Another Transitional MSP System

- Low-mass X-ray binary with *Fermi* LAT counterpart: 2FGL J1227.7–4553 (Hill et al. 2011; de Martino et al. 2010,2013)
- In Nov/Dec 2012, optical flux declined by ~ 1.5 mag (Bassa et al. 2014)
- X-ray flux decreased by $\sim \times 10$
- Optical emission lines disappeared (de Martino et al. 2015)
- Radio and γ -ray pulsations detected in non-accreting state at $P=1.69$ ms (Roy et al. 2014; Johnson et al. 2015)

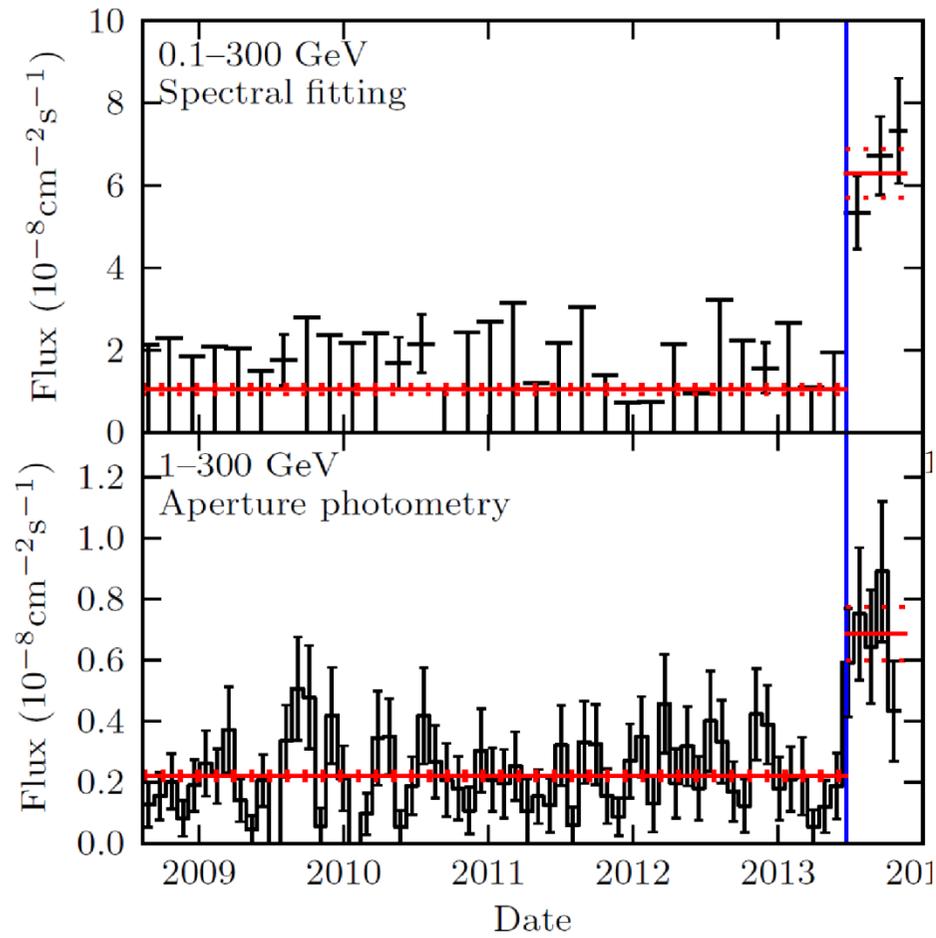


Transition from LMXB to “redback” radio MSP

XSS J12270-4859

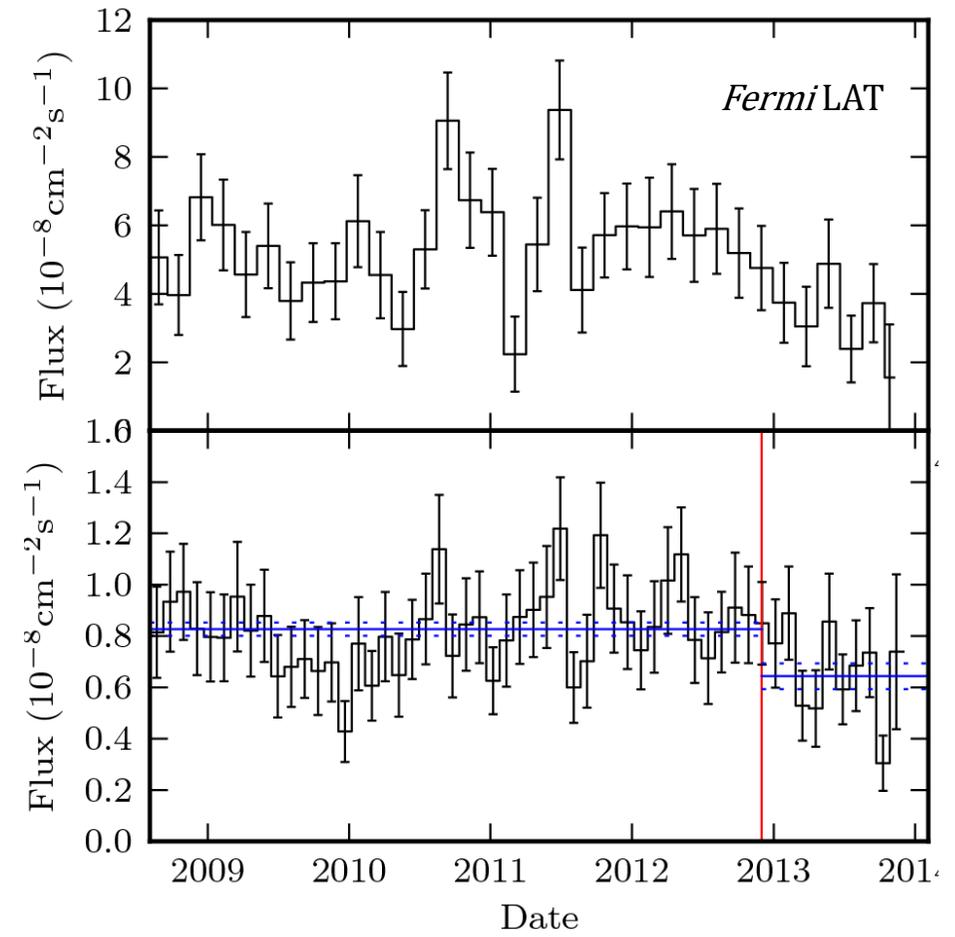


PSR J1023+0038

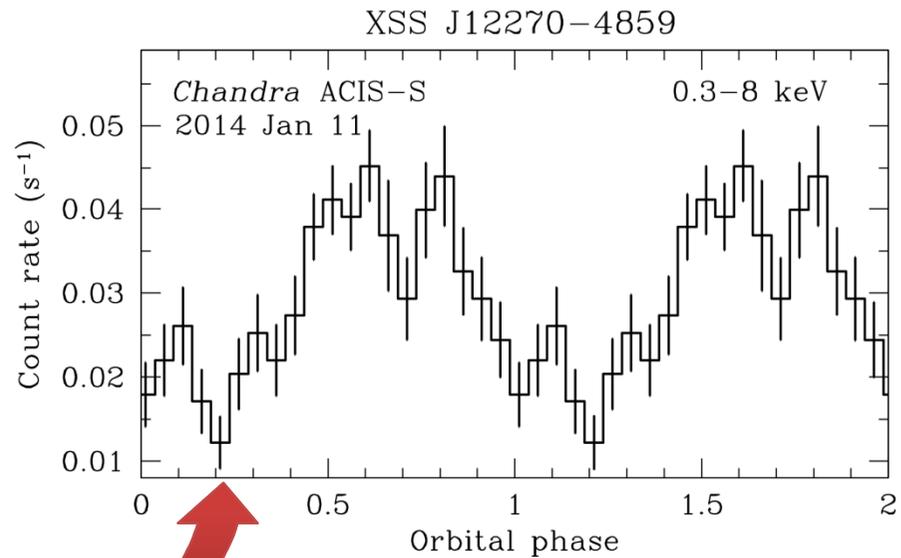
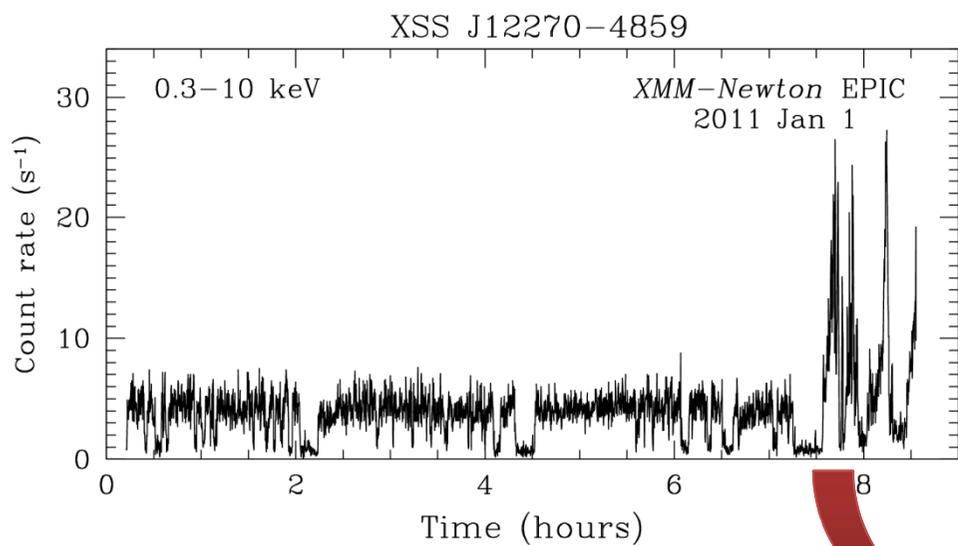
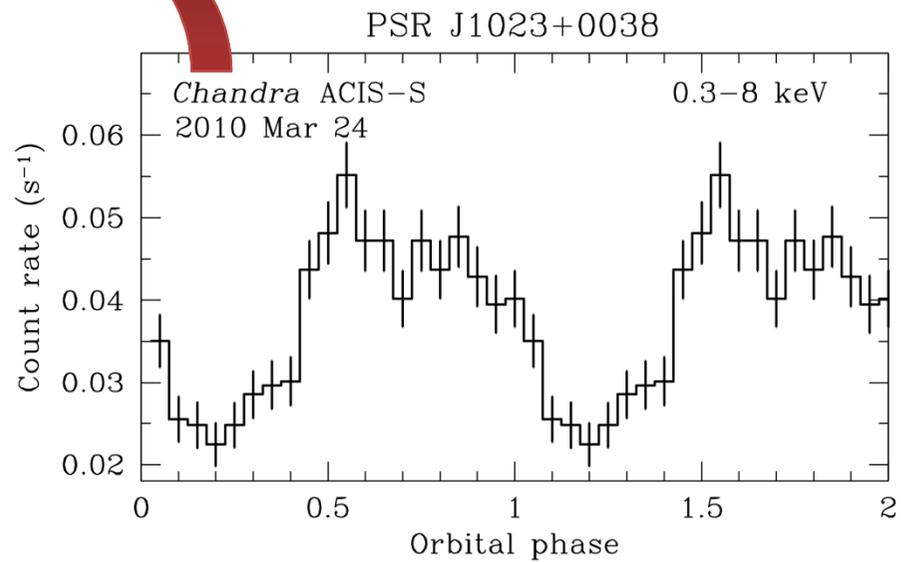
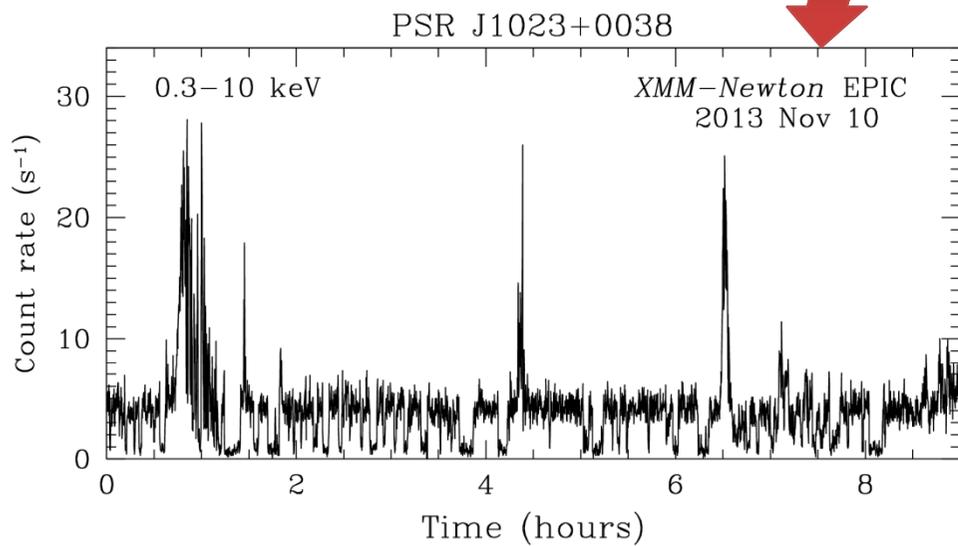


Stappers et al. (2013)

XSS J12270-4859

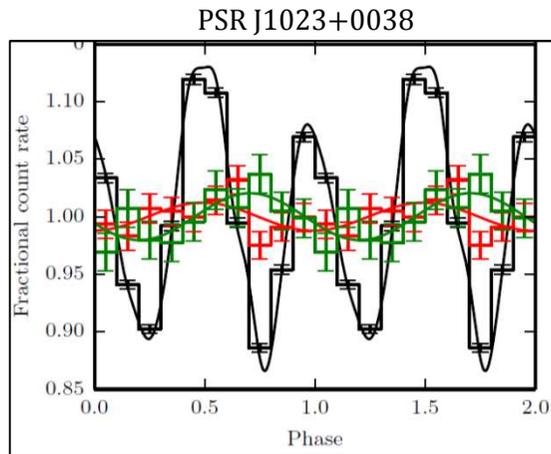


Courtesy of A. Archibald

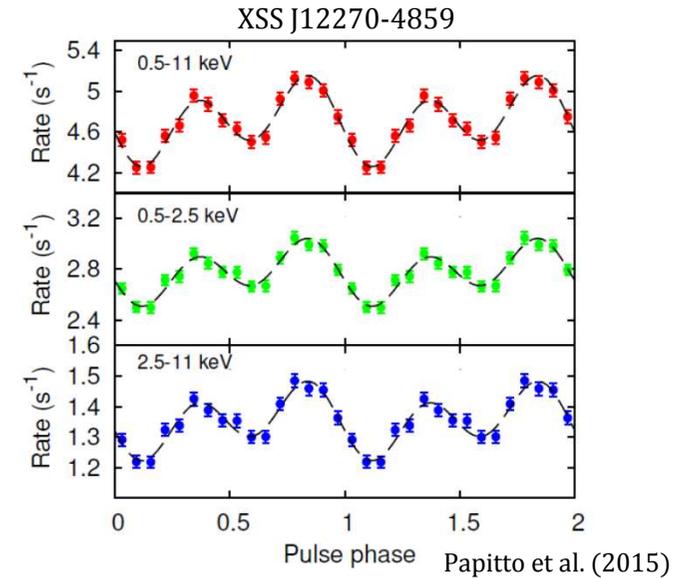


Accretion-powered Coherent X-ray Pulsations!

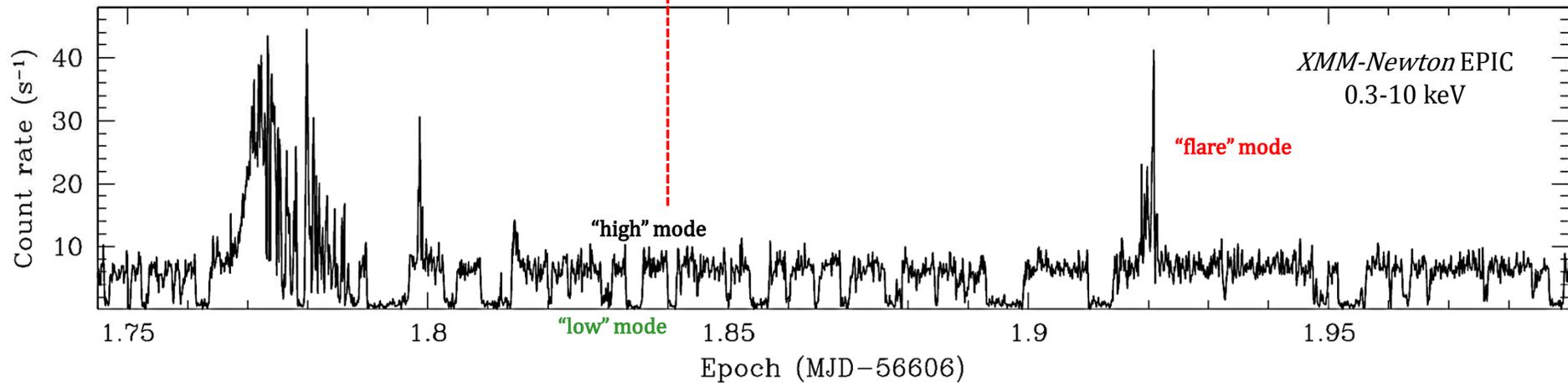
- X-ray pulsations only in “high” mode \Rightarrow channeled accretion onto neutron star polar caps at $L_x \approx 10^{33} \text{ erg s}^{-1}$ ($\sim 10^{-5} L_{\text{edd}}$)



Archibald et al. (2015)

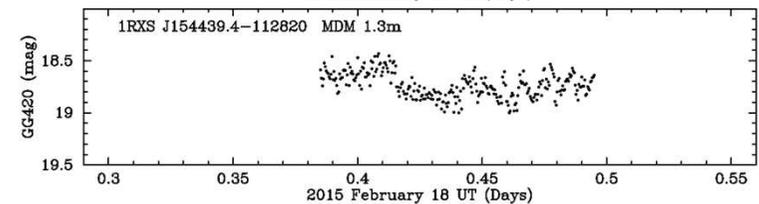
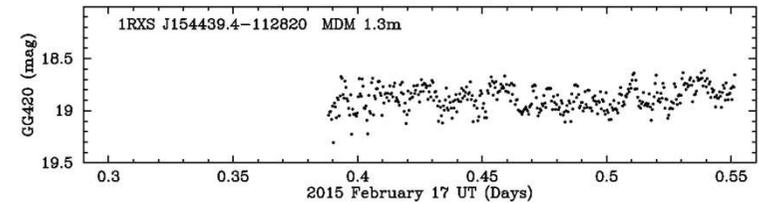
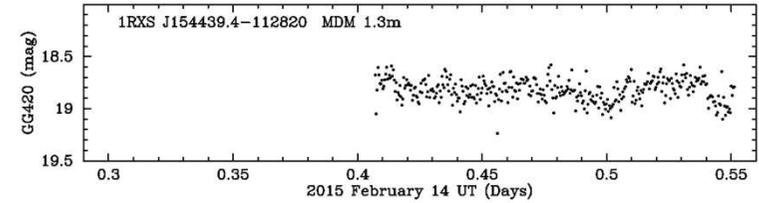
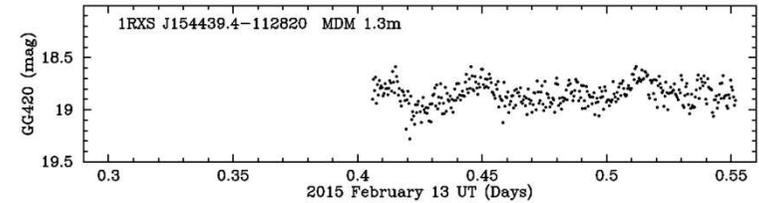
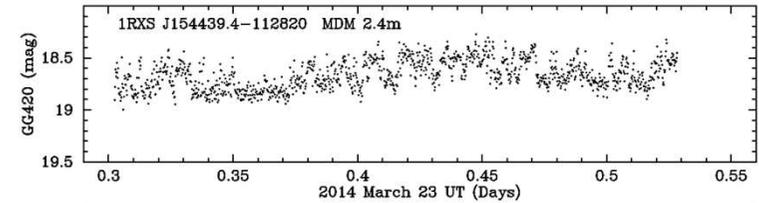
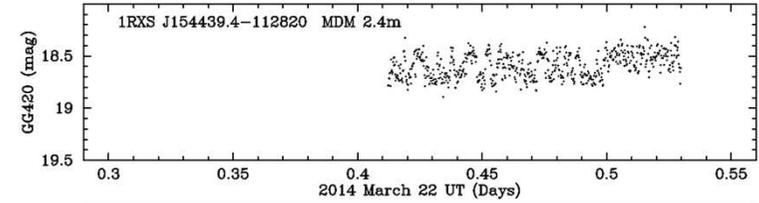
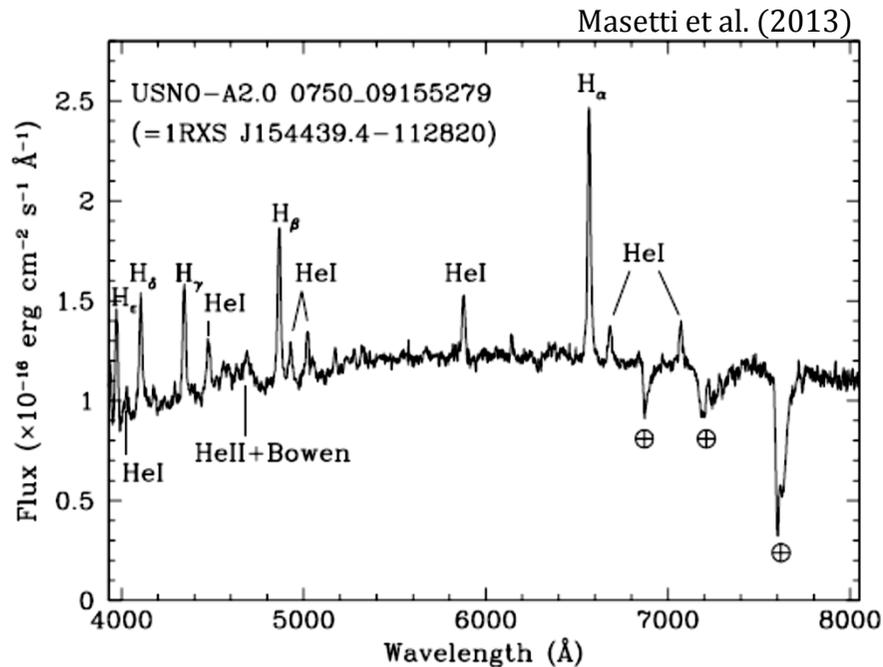


XMM-Newton EPIC
0.3-10 keV



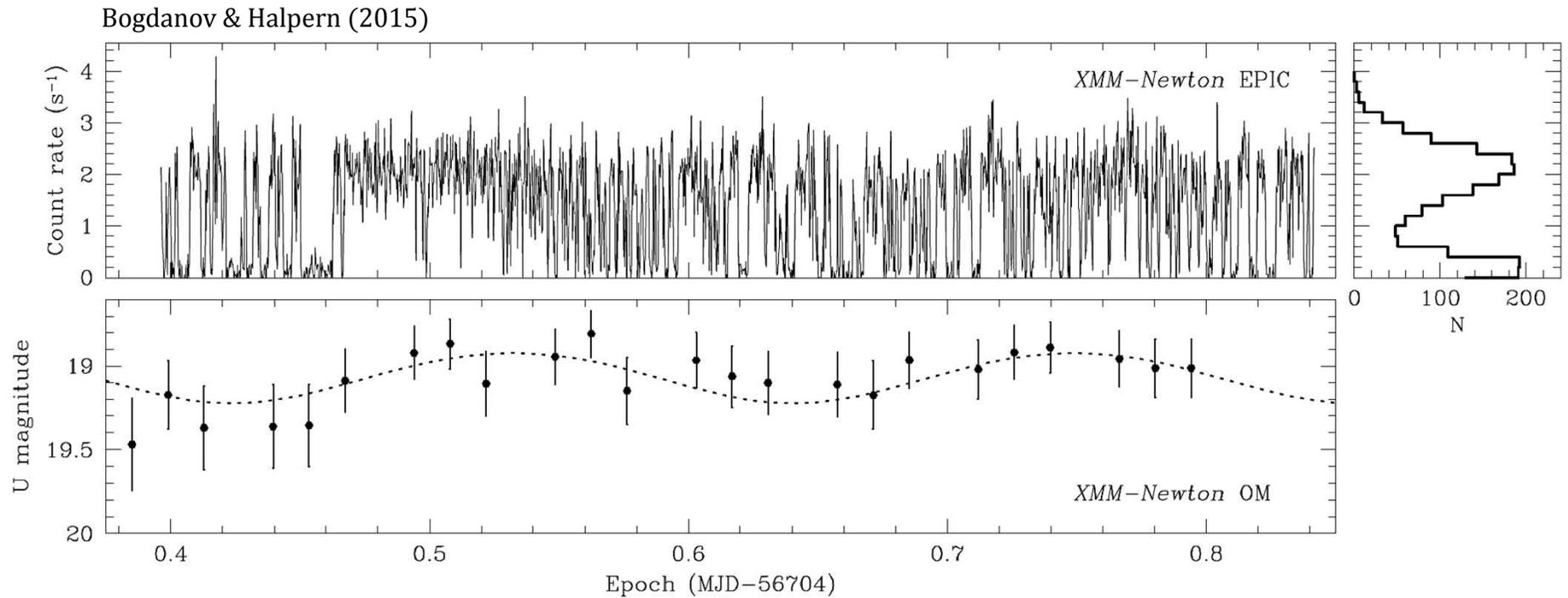
1RXS J154439.4–112820 / 3FGL J1544.6–1125: A New Transitional MSP Candidate

- ☑ Positional coincidence with unassociated *Fermi* LAT source
- ☑ CV-like optical spectrum
- ☑ Rapid optical/UV variability with modes



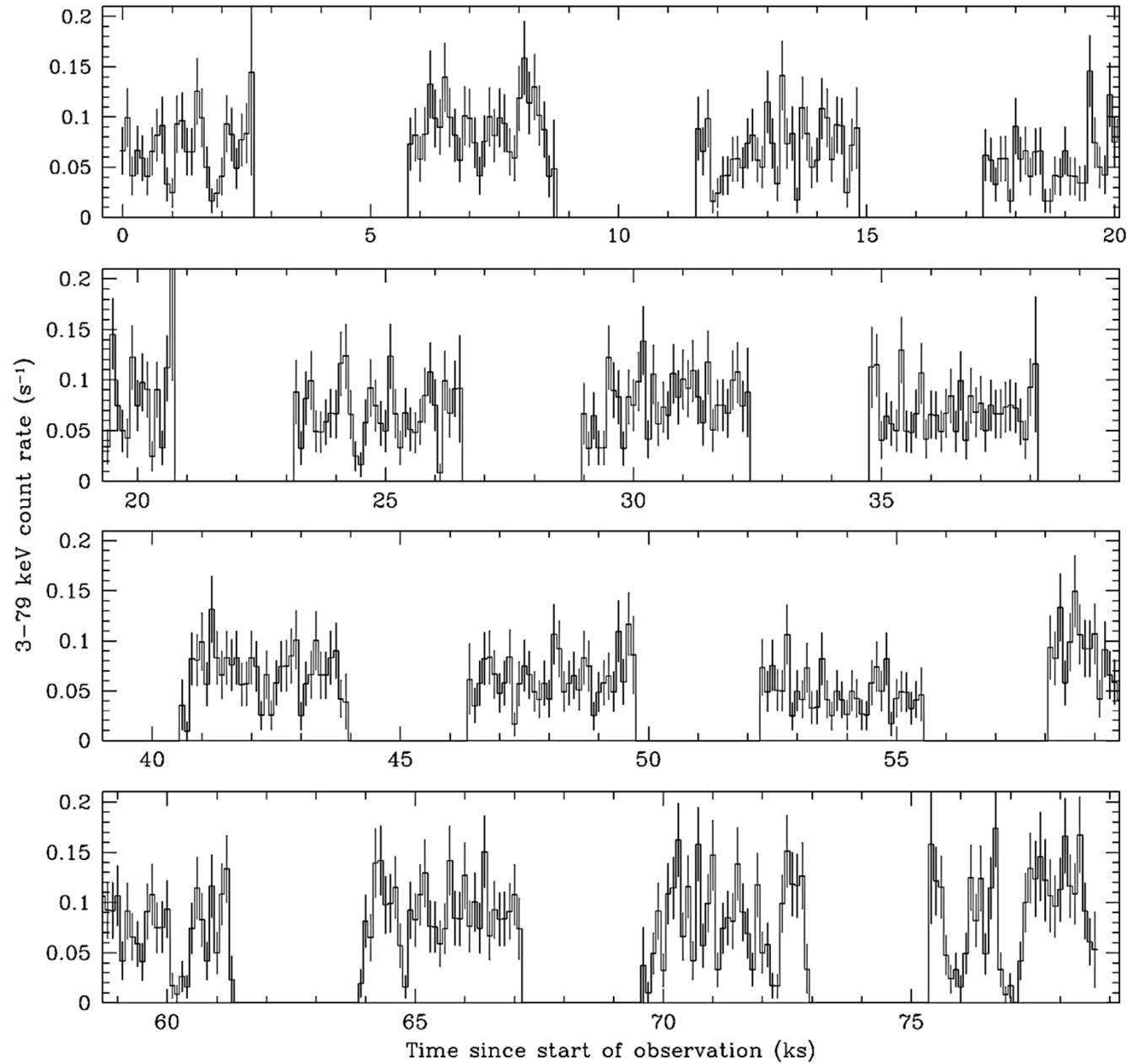
1RXS J154439.4–112820 / 3FGL J1544.6–1125: A New Transitional MSP Candidate

- ☑ Moderately bright X-ray emission with rapid mode switching and flux bimodality

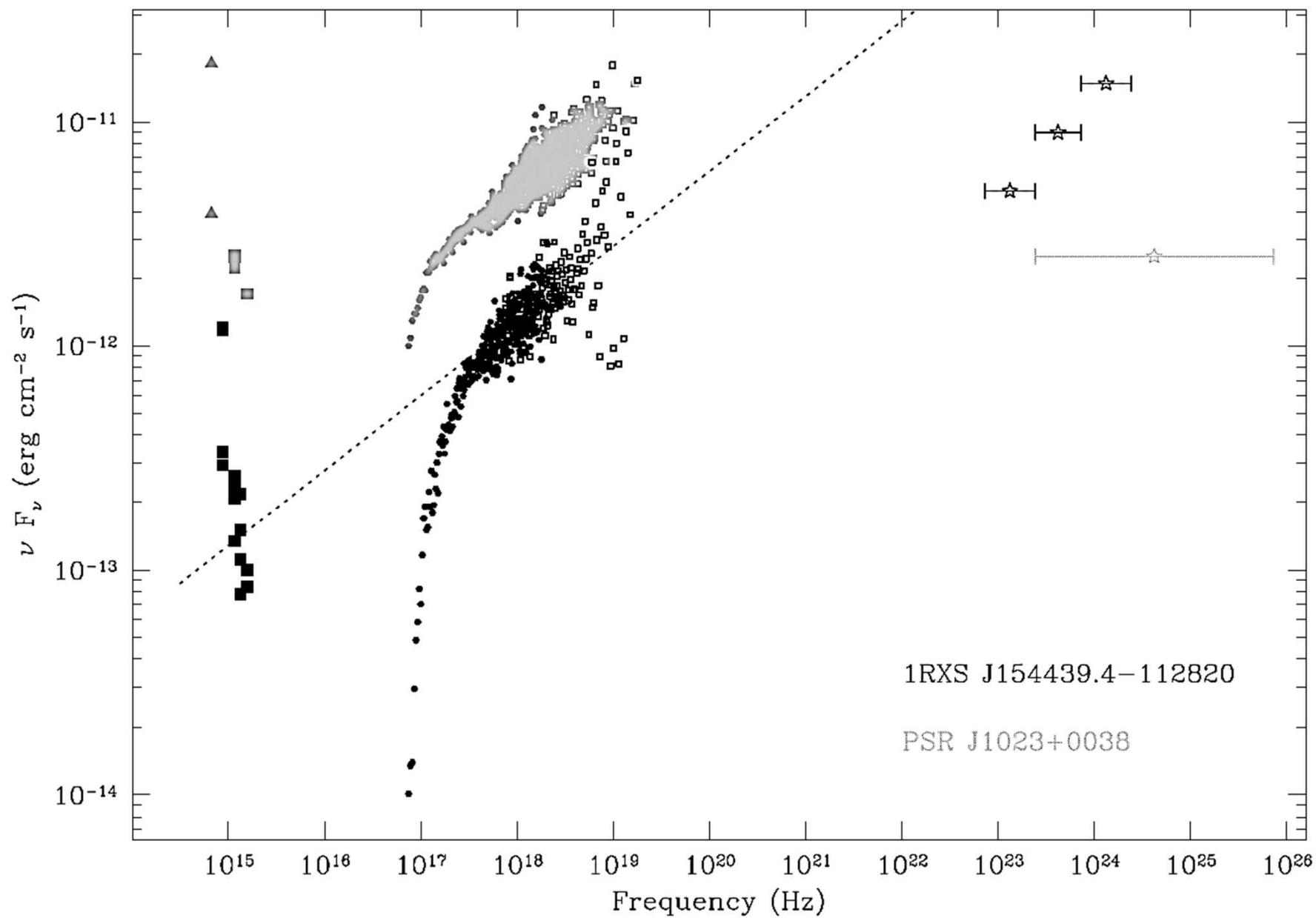


1RXS J154439.4-112820

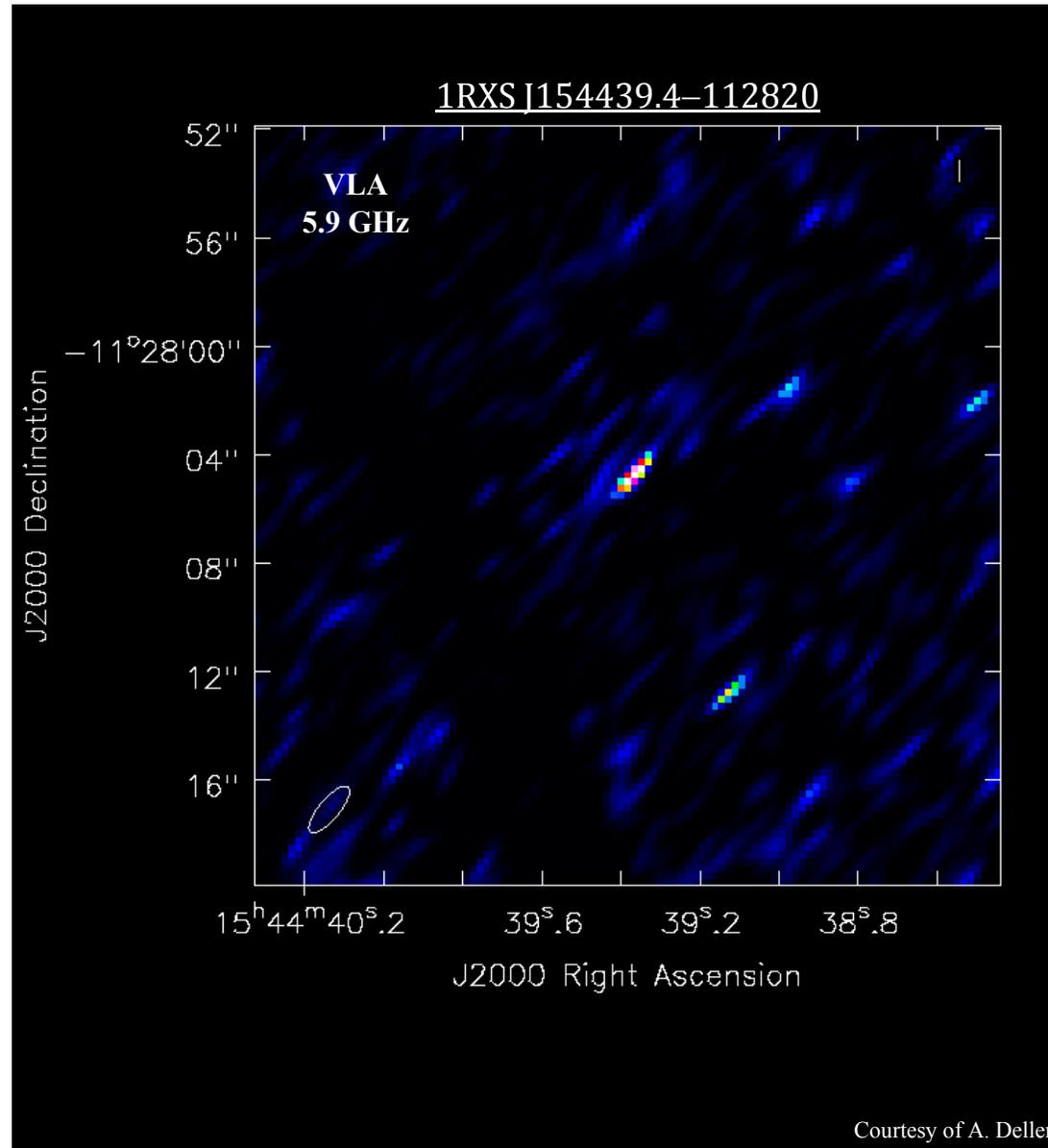
NuSTAR
FPMA+FPMB
3-79 keV



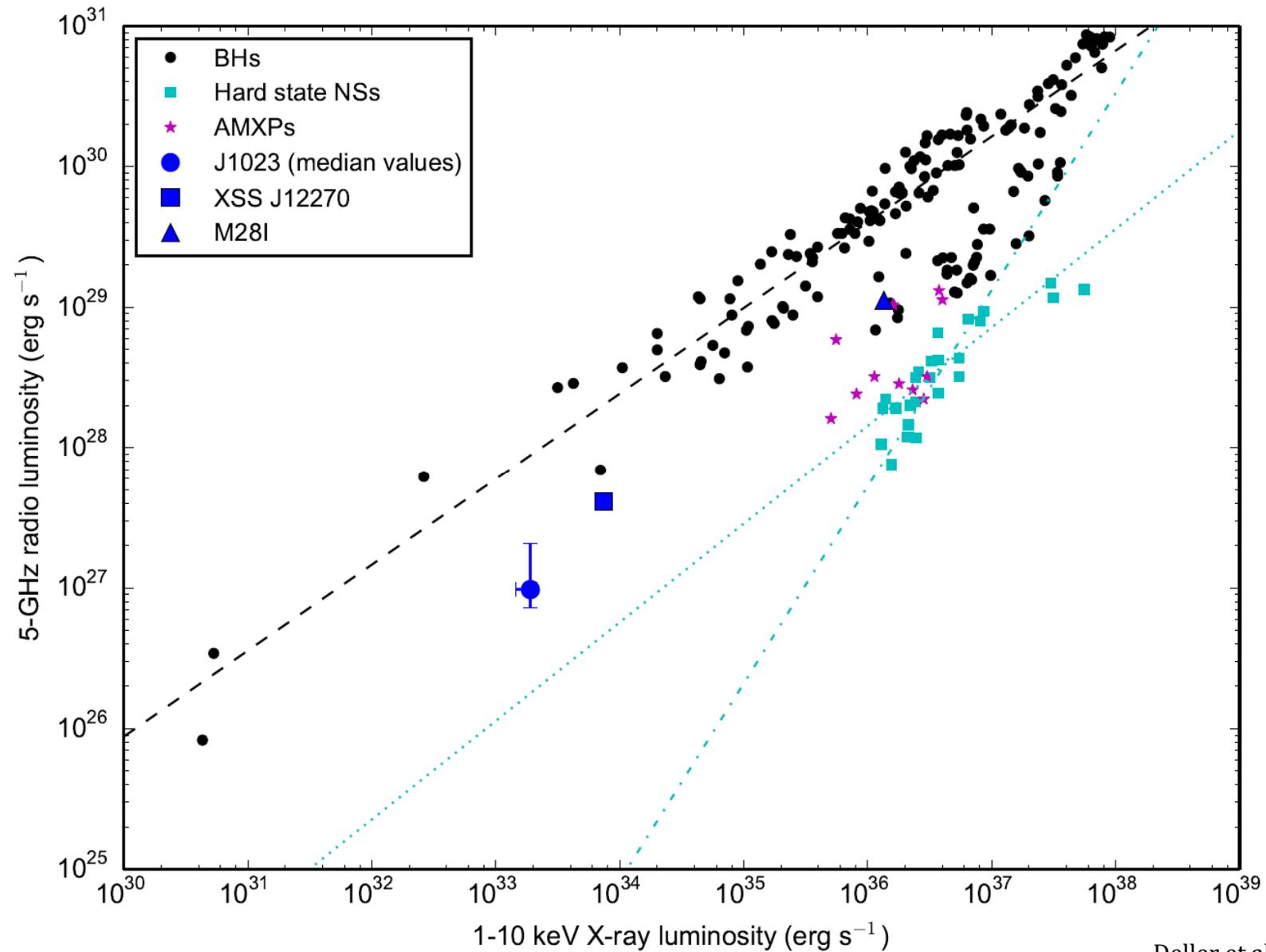
1RXS J154439.4–112820 vs PSR J1023+0038



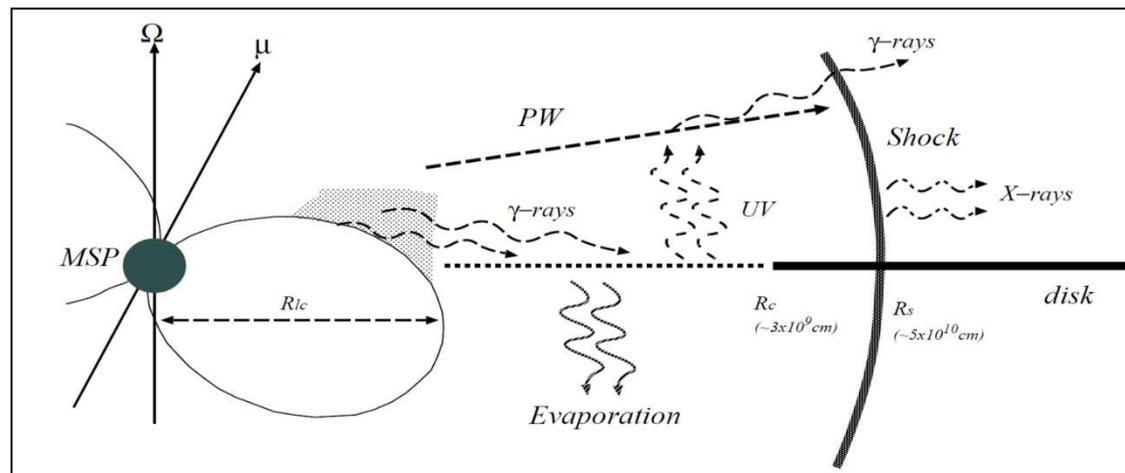
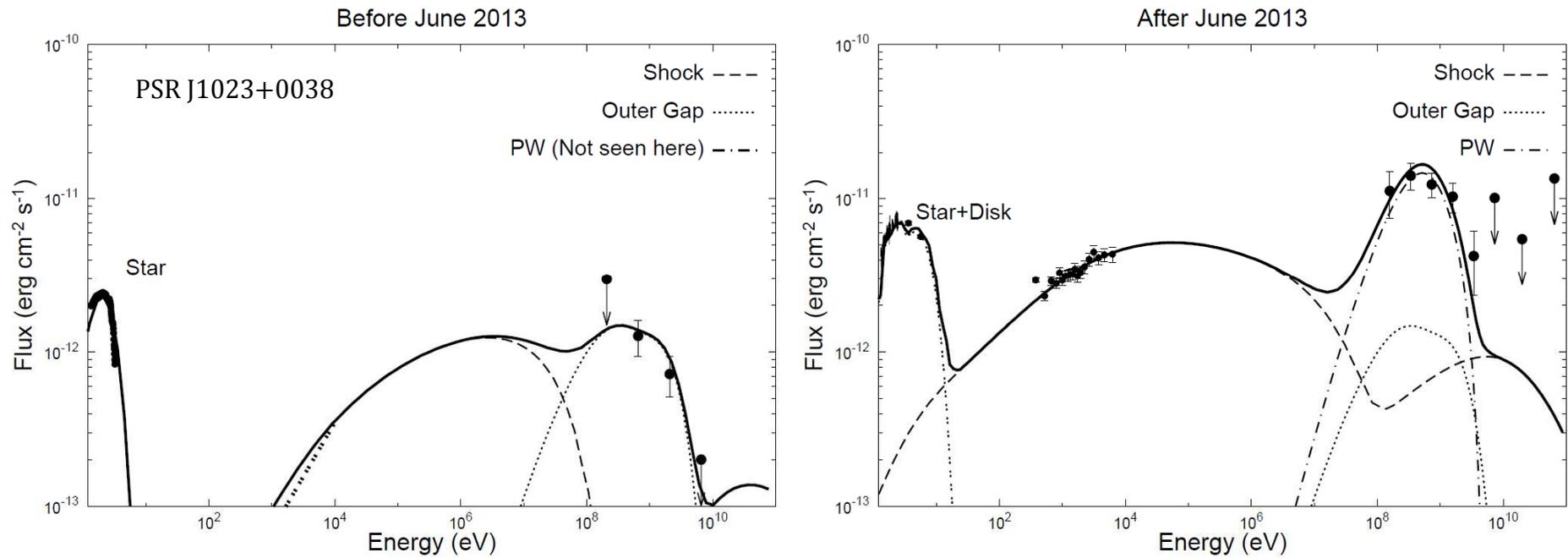
Flat-spectrum radio source



An X-ray/Radio Luminosity Correlation for accreting MSPs?

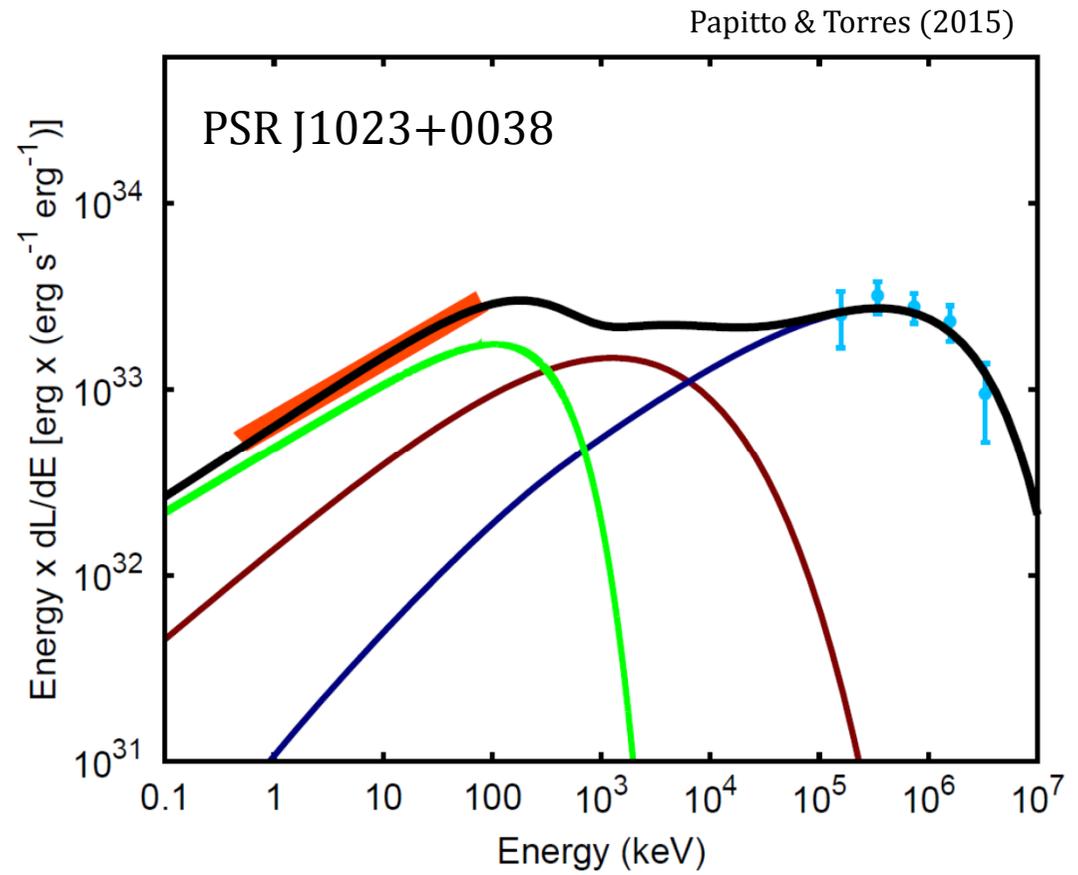
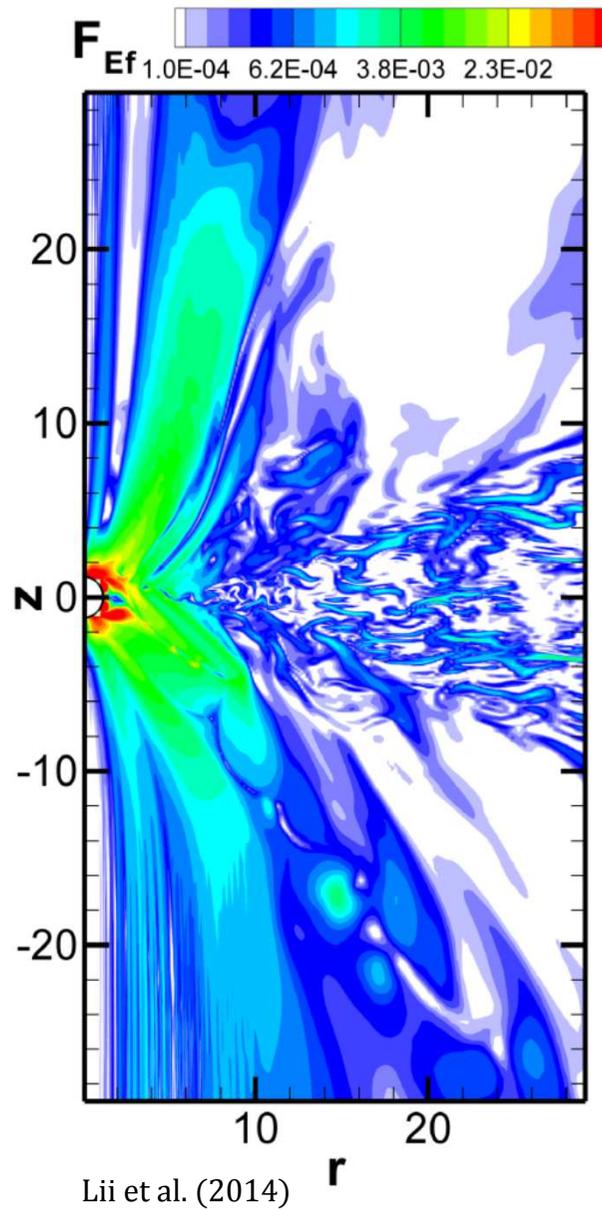


Origin of γ -rays: Intra-binary Shock?



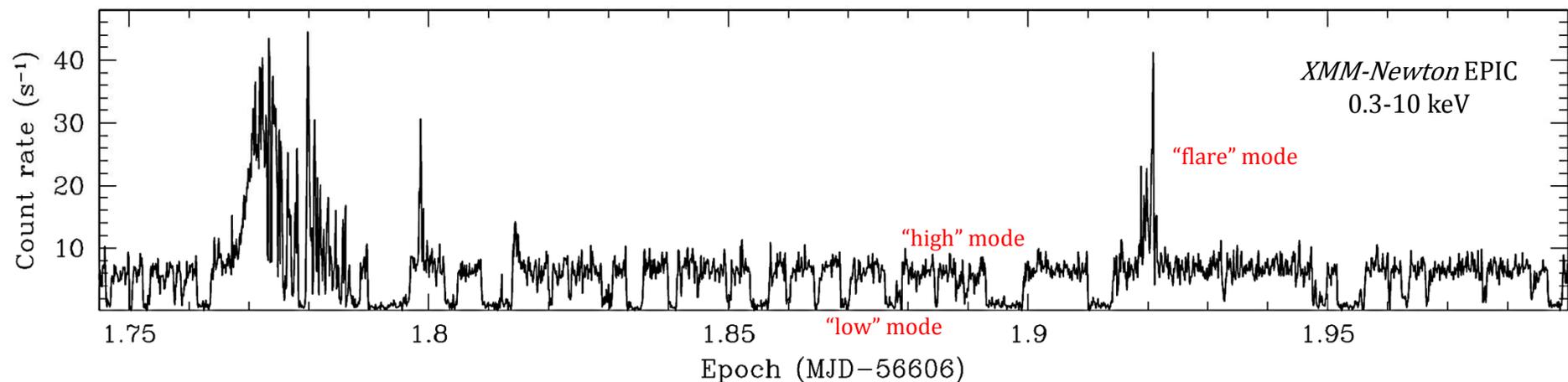
Takata et al. (2014)

Origin of γ -rays: Propeller Mechanism?



Transitional Millisecond Pulsars

- Lack of radio pulsar emission when accreting – enshrouding or quenching due to accretion?
- Flat-spectrum radio continuum emission – jet-like outflow?
- X-ray mode switching – emptying and refilling of inner accretion disk or interruptions in low-level accretion?
- X-ray/optical flares – enhanced accretion onto neutron star?
- GeV γ -ray emission – intra-binary shock or propeller ejection?



Conclusions

- Transitional MSPs (tMSPs): only known variety of γ -ray-emitting low-mass X-ray binaries
- Only 3 *bona fide* tMSPs identified so far
 - ⇒ Necessary to extend the sample of transitional MSPs
- At present, only PSR J1023+0038 in low-luminosity accreting state - plus 1RXS J154439.4–112820
- Detailed behavior of tMSP accreting state is telling us something important about disk/magnetosphere interactions and jet production
 - ⇒ Further multi-wavelength studies of known tMSPs are essential